2 METHODS & OPERATIONAL BACKGROUND

The use of Pacific Reef Assessment and Monitoring Program (Pacific RAMP) field collection methodologies produces an interdisciplinary series of integrated ecosystem observations of coral reefs around ~ 50 islands, atolls, and shallow-water banks of the Mariana Archipelago, American Samoa, the Hawaiian Archipelago, and the Pacific Remote Islands Marine National Monument. Pacific RAMP data collections, led by the Coral Reef Ecosystem Division (CRED) of the NOAA Pacific Islands Fisheries Science Center (PIFSC), are designed to characterize the spatial and temporal variability of the distribution, abundance, and diversity of corals, algae, other macroinvertebrates, and fishes in the context of their benthic habitats and oceanographic environments within in the scope of these surveys.

This report provides information from Pacific RAMP research cruises conducted in 2003, 2005, and 2007 in the Mariana Archipelago. To document the nature and temporal variation of the data gathered and to provide a context for how surveys were performed, the operational background of these 3 Mariana Archipelago RAMP (MARAMP) expeditions and details on the suite of assessment and monitoring methods employed during these cruises are presented in this chapter. Descriptions of data collection and processing methodologies are also supplied.

Although CRED collects most of its ecological and oceanographic observations every 2 years during Pacific RAMP research cruises, time-series observations of some key environmental conditions that influence reef processes are also made continuously by an array of moored oceanographic and bioacoustic instruments deployed and maintained as part of the NOAA Coral Reef Watch (CRW) program. These biological and environmental observations are further complemented by a suite of benthic habitat mapping products developed collaboratively by CRED and the Biogeography Branch of the NOAA Center for Coastal Monitoring and Assessment (CCMA), National Centers for Coastal Ocean Science. Collectively, CRED's Pacific RAMP, CRW, and benthic-habitat-mapping efforts are part of the NOAA Coral Reef Ecosystem Integrated Observing System (CREIOS) in the Pacific.

There are several primary objectives for these Pacific RAMP activities in the U.S. Pacific islands:

- Conduct benthic habitat mapping of reefs and submerged banks using ship- and launch-based multibeam sonars (echosounders), underwater towed-camera systems, and towed-diver surveys for characterizing the benthic environments that provide habitat and shelter for reef biota

- Conduct nearshore and offshore oceanographic and water-quality surveys and deploy a variety of surface and subsurface oceanographic and bioacoustic instruments to quantify, assess, and gain a better understanding of the overall hydrographic and bioacoustic parameters that influence reef biota

- Employ complementary and overlapping methods to assess and monitor species composition, abundance, percentage of cover, size distribution, diversity, and general health of fishes, corals, algae, and other macroinvertebrates in shallow-water (< 35 m) habitats

- Assess and monitor diseases of corals and coralline algae

- Conduct broadscale towed-diver surveys that provide a spatial assessment of the composition and condition of shallow-water benthic habitats and of the general distribution and abundance patterns of ecologically or economically important macroinvertebrates and reef fishes (> 50 cm in total length)

- Ascertain the existence of threats to the health of coral reef resources from natural or anthropogenic sources

Integrated ecosystem observations and monitoring of this scope were unprecedented in the waters of the Mariana Archipelago, which includes the territory of Guam and the Commonwealth of the Northern Mariana Islands (CNMI). As such, the initial interdisciplinary research expeditions for the Pacific RAMP were exploratory in nature, often providing the first-ever baseline assessments of reef resources in these mostly remote and uninhabited regions of the Pacific. As analyses of these initial baseline assessments have progressed, the Pacific RAMP has shifted to a long-term ecosystem monitoring phase. The suite of methods used by this program also has steadily evolved to improve the quality of the data. The comprehensive nature of this interdisciplinary research program is evident in Table 2a, which summarizes by year survey efforts in the Mariana Archipelago.

Table 2a. Survey efforts in the Mariana Archipelago summarized by year for the period of 2003–2007. Activities included benthic habitat mapping with multibeam echosounders; towed optical assessment device (TOAD) surveys; Rapid Ecological Assessment (REA) surveys; towed-diver surveys; shallow-water and deepwater conductivity, temperature, and depth (CTD) casts; water-quality sample collection, and deployment of a suite of moored oceanographic and bioacoustic instruments. Vessels included the NOAA Ships *Oscar Elton Sette* and *Hi`ialakai* and the R/V *Acoustic Habitat Investigator* (*AHI*), and in 2004 TOAD surveys were conducted from a chartered 19-m boat.

Survey Type	Survey Detail	Year				Total
		2003	2004	2005	2007	
	Vessels	OES/AHI	Charter	Hi'i	Hi'i/AHI	
Multibeam	Total Survey Area (km^2)	244.2	–	–	1,2992.0	**1,3236.2**
TOAD	Number of Surveys	110	41	–	–	**151**
	Total Length (km)	72.05	136.26	–	–	**208.31**
REA–Fish	Number of Surveys	72	–	74	66	**212**
REA–Benthic	Number of Surveys	85	–	74	67	**226**
Towed Diver	Number of Surveys	161	–	136	115	**412**
	Total Survey Area (ha)	309.9	–	267.6	262.0	**839.5**
CTD–Shallow water	Number of Casts	249	–	327	273	**849**
CTD–Deep water	Number of Casts	–	–	70	36	**106**
Water Quality	Number of Water Samples	–	–	57	69	**126**
Moored Instruments	Number Deployed	19	1	28	48	**96**
	Number Retrieved	–	1	14	28	**43**

2.1 Operational Background

As part of this Pacific-wide monitoring effort, CRED conducted its first MARAMP cruise in 2003 with subsequent cruises in 2005 and 2007. Partners from local resource management agencies—including scientists and managers from Guam's Division of Aquatic and Wildlife Resources (DAWR) and Bureau of Statistics and Plans (BSP), the Guam Environmental Protection Agency (GEPA), the University of Guam (UG), and the CNMI's Division of Fish and Wildlife (DFW), Division of Environmental Quality (DEQ), and Coastal Resources Management (CRM) Office, as well as the National Park Service (NPS) and Western Pacific Fishery Management Council (WPFMC)—worked alongside CRED scientists to determine and establish monitoring sites and plan and conduct surveys.

The following individuals from the CNMI and Guam participated in the planning or implementation of MARAMP cruises:

- **2003:** Fran Castro (DEQ), Peter Houk (DEQ), Trina Leberer (DAWR), Kate Moots (DFW), and Michael Trianni (DFW)
- **2005:** Fran Castro (DEQ), Tony Flores (DFW), Peter Houk (DEQ), John Iguel (DEQ), Andrew Kerr (UG), Edson Limes (DEQ), Nick Pioppi (UG), Valerie Brown (DAWR), Qamar Schuyler (DEQ/CRM/DFW), Michael Tenorio (DFW), Brent Tibbetts (DAWR), and Michael Trianni (DFW)
- **2007:** Valerie Brown (NOAA Fisheries Pacific Islands Regional Office, Guam), Peter Houk (DEQ), Edson Limes (DEQ), Allison Palmer (NPS Guam), Tom Schils (UG), John Starmer (CRM), and Michael Tenorio (DFW)

Planning of MARAMP cruises also included the following individuals: John Calvo (WPFMC), Erica Cochrane (CRM), Ken Cochrane (CRM), Gerry Davis (DAWR), Mike Gawel (GEPA), Jay Gutierrez (DAWR), Sylvan Igisomar (DFW), John Joyner (CRM), Becky Lizama (CRM), Evangeline Lujan (BSP), Dwayne Minton (NPS), Frank Rabauliman (DEQ), Bob Richmond (UG), Peter Schupp (UG), and Adam Turner (advisor to CNMI Office of the Governor).

These first 2 MARAMP expeditions were conducted from the NOAA Ship *Oscar Elton Sette* between August 19 and September 30, 2003, and between August 16 and October 9, 2005. The third cruise was conducted from the NOAA Ship *Hi`ialakai* between May 12 and June 9, 2007 (Fig. 2.1a). This change to a different time of year in 2007 was made to better avoid the typhoon season and, thus, lower the probability of weather disrupting a cruise. This shift to a different season led to significant differences in oceanographic and biological observations.

The *Oscar Elton Sette* and *Hi`ialakai*, as well as their officers and crews, have different capabilities and limitations. The *Oscar Elton Sette* can accommodate a complement of 20 scientists and carry and deploy multiple small boats. During the MARAMP 2003 expedition, CRED's 8-m multibeam survey launch R/V *Acoustic Habitat Investigator* (*AHI*) was transported to Saipan, launched, and recovered in Guam. The *AHI* was carried on the stern of the *Oscar Elton Sette* and deployed using this ship's crane. The use of the *Hi`ialakai* in 2007 increased the maximum complement to 22 scientists and significantly improved the ability of CRED to conduct benthic habitat mapping missions. The *Hi`ialakai* had hull-mounted shallow-water and deepwater multibeam systems and was able to carry the *AHI* in dedicated davits, which allowed for deployment of the *AHI* at sea. The *Hi`ialakai* is also equipped with diesel-powered, 8-m and 10-m small boats, a cascade nitrox compressor system, and a permanently installed diving recompression chamber.

Figure 2.1a. The NOAA Ships (*left*) *Oscar Elton Sette* and (*right*) *Hi`ialakai* were used to conduct MARAMP cruises in 2003, 2005, and 2007. *NOAA photos*

CRED has also increased its small-boat and dive-support capabilities with the addition of two 6-m boats (SAFE Boats International) and a portable cascade Nitrox compressor system. Over the MARAMP survey period of 2003–2007, support of diving operations was enhanced as the NOAA Dive Center endorsed the transition from exclusive use of decompression tables to the standard use of dive computers and began providing a portable recompression chamber aboard the *Oscar Elton Sette* during cruises that required extensive diving operations.

2.2 Benthic Habitat Mapping and Characterization

Accurate, high-resolution benthic habitat maps are essential tools for the effective conservation and management of coral reef ecosystems. CRED, through its Pacific Islands Benthic Habitat Mapping Center (PIBHMC), conducts mapping operations during dedicated mapping cruises, expeditions that combine Pacific RAMP and mapping objectives, and cruises that piggyback mapping operations with other missions. Using data collected during these cruises, a suite of thematic map products are created and made available to resource management agencies, researchers, and the general public.

Bathymetry is the study of the seafloor, and bathymetric data can be used to illustrate underwater terrain. High-resolution bathymetric data collected with multibeam echosounders serve as the primary base layer for CRED's benthic habitat mapping. The highly accurate and detailed maps generated from these data are useful for a number of management and research applications. Maps derived from these bathymetric data illustrate or highlight other seafloor characteristics, including slope, rugosity (a measure of topographic roughness), and bathymetric position index (BPI) zones (a BPI defines elevations of locations in reference to the overall seafloor).

In addition to bathymetric and derived data products, modern multibeam echosounders produce data about the intensity of returning acoustic signals (backscatter) that provide an indication of the roughness and hardness of the seafloor. Backscatter and bathymetry data, for example, were used to produce hard–soft substrate maps. Used in various combinations, depth, slope, rugosity (roughness), and backscatter intensity can yield information about seafloor characteristics relevant to specific groups of organisms, and such information can be used to identify and delineate the benthic habitats of key organisms.

Optical data are used to validate (or ground truth) interpretations of acoustically derived information. Toward this end, towed optical assessment device (TOAD) surveys and towed-diver surveys routinely produce observation data, still photographs, and video imagery of the seafloor. Optical data are also useful for discerning seabed information in very shallow waters, where logistical constraints may hinder or prevent multibeam acquisition.

2.2.1 Operational Background and Logistics

The U.S. Coral Reef Task Force (CRTF) identified mapping of all U.S. coral reef habitats as one of its highest priorities in the 2000 National Action Plan to Conserve Coral Reefs. Meanwhile, NOAA's CRCP established a goal to map all U.S. coral reef areas to assist in the conservation and management of U.S. coral reefs. In support of these goals, CRED and the CCMA Biogeography Branch have been leading efforts to produce benthic habitat maps of U.S. coral reef areas from the shoreline to moderate depths (≤ 1000 m). The Biogeography Branch has been leading collaborative efforts to develop shallow-water benthic habitat maps using aerial and satellite-based methods. Because of visibility constraints, these techniques are best suited for shallow-water habitats (depths ≤ 20 m). CRED has been leading efforts using multibeam acoustic echosounders and optical assessment technologies to extend existing shallow-water maps to moderate depths (~ 15–1000 m) where aerial- and satellite-based techniques are less suitable.

The NOAA Ships *Oscar Elton Sette* and *Hi`ialakai* were used to support mapping operations in the Mariana Archipelago on 3 expeditions conducted in 2003, 2005, and 2007, and the R/V *AHI* was deployed in 2003 and 2007 to conduct shallow-to-moderate depth habitat mapping.

A variety of operational scenarios have been developed to optimize the efficiency of mapping operations. In 2003, the R/V *AHI* was offloaded from the *Oscar Elton Sette* in Saipan and picked up later in Guam; *AHI*-based multibeam mapping operations were conducted independently at Saipan, Tinian, Rota and Guam while the *Oscar Elton Sette* worked in more remote locations. During these operations, the *AHI* also performed a reconnaissance survey of Saipan Harbor at the request of the harbormaster of the Commonwealth Port Authority. Optical-validation data were collected during nighttime hours using the TOAD camera-sled deployed from the *Oscar Elton Sette* at depths of 20–150 m and during daylight hours using launch-based towed-diver surveys at depths of 3–30 m.

In 2004, after learning about the multibeam and optical data collected by CRED in Saipan Harbor and Garapan Anchorage (where the U.S. Military Sealift Command [MSC] routinely anchors prepositioned supply ships), the U.S. Naval Facilities Engineering Command (NAVFAC) and MSC funded CRED collection of an additional 123 linear km of optical data during an independent shore-based deployment. In 2005, multibeam bathymetry and backscatter and optical data were used to analyze the substrates in the Garapan Anchorage and to produce a report for the NAVFAC and MSC (Rooney et al. 2005).

Because of shipboard staffing, funding, and limitations on the *Oscar Elton Sette*, no multibeam or TOAD operations were conducted during the MARAMP 2005 expedition. Still, routine towed-diver surveys were performed. During MARAMP 2007 cruises aboard the *Hi`ialakai*, shipboard multibeam mapping surveys were conducted primarily during nighttime hours to avoid interfering with daytime reef ecosystem monitoring and nearshore oceanographic surveys that require small-boat and diver-based operations. R/V *AHI*-based mapping operations were conducted during daylight hours to perform multibeam surveys in shallow, nearshore waters inaccessible to the *Hi`ialakai*. In addition, 10 d of time on the R/V *AHI* were dedicated to conducting surveys of the harbors of Saipan, Tinian, and Rota to International Hydrographic Organization standards in collaboration with NOAA's Office of Coast Survey and National Geodetic Survey as well as the CNMI Commonwealth Port Authority and in support of safe navigation in CNMI waters.

Operationally, both multibeam surveying and optical data collection have depth limitations. As a general rule, multibeam surveys by CRED have focused on depths of ~ 15–1000 m. This 15-m inshore limit is based on (1) safety concerns relating to increased risks of groundings or breaking waves in shallow water and (2) significant decreases in mapping efficiencies because the area that a surface vessel can map decreases proportionally to depth.

Similarly, optical data collection using ship-based TOAD surveys has been limited to depths of ~ 20–150 m, because of the depth limitations of instruments and ship safety concerns. Towed-diver surveys provide optical data to a maximum depth of 30 m. Ship- and launch-based multibeam surveying, as well as TOAD and towed-diver survey procedures, adhere strictly to NOAA safety policies applicable to ship, small-boat, and scuba-diving operations.

2.2.2 Acoustic Mapping

Equipment

The *Hi`ialakai* is equipped with a Kongsberg 300-kHz EM 3002D multibeam sonar that can map at depths of ~ 15–150 m and a Kongsberg 30-kHz EM 300 multibeam sonar that can map at depths of ~ 50–3000 m. Because the *Hi`ialakai* had standing orders that limit the minimum depth of nighttime operations to 200 m on almost all surveys, the EM300 was the only sonar used in 2007. The *AHI* is equipped with a 240-kHz Reson SeaBat 8101 ER multibeam sonar that can map at depths of ~ 10–300 m. When used in conjunction with the *Hi`ialakai*, the *AHI* can be deployed and recovered in locations far from sheltered harbors, making shallow-water surveys possible throughout remote areas of the U.S. Pacific islands (Fig. 2.2.2a).

Hand-held, single-beam echosounders were used in 2003 from small boats to survey the remote areas of Zealandia Bank, Stingray Shoal, Supply Reef, Pathfinder Reef, and 2 unnamed banks. These surveys were performed because rudimentary bathymetric data were needed to locate habitats for potential ecosystem assessments.

Figure 2.2.2a. The survey launch R/V *AHI* and NOAA Ship *Hi`ialakai* are outfitted with 3 multibeam echosounders that facilitate mapping at depths of ~ 15–3000 m. *NOAA photo*

Survey Design

The quality and geographic coverage of existing bathymetric data, as well as consultation with key resource managers and stakeholders, were used to determine mapping survey priorities. Existing nautical charts served as the primary base for the initial planning process. Prior to 2003, almost no modern shallow bathymetric data existed for the Mariana Archipelago, except for a limited amount of then-unavailable light detection and ranging, or lidar, data collected by the U.S. Navy. Most existing nautical charts were based on Japanese surveys conducted before and during World War II. In 2003, the Saipan harbormaster requested NOAA to perform a survey of Saipan Harbor because of suspected shoal soundings in the channels and hazards to navigation.

During the cruise in 2003, the R/V *AHI* mapped around Saipan and Tinian with almost complete coverage at depths from 20 to 250 m. The southern shore of Rota in the Sasanhaya Fish Preserve and the northern shore of Guam in the Pati Point Marine Preserve were mapped after consultation about priority survey areas with CNMI and Guam officials.

During the first of 2 cruises in 2007 in the southern part of the Mariana Archipelago, CRED personnel aboard the *Hi`ialakai* conducted surveys at depths > 300 m, with some deeper than 1000 m, around most of Guam, Rota, Aguijan, Tinian, and Saipan. During the second of the 2 cruises in 2007 around this archipelago's more isolated northern islands, *AHI* surveys were conducted at depths of 15–300 m around the islands of Sarigan, Guguan, Alamagan, Pagan, Agrihan, Asuncion, Maug, and Farallon de Pajaros as well as on Zealandia Bank and Supply Reef. Multibeam operations on the *Hi`ialakai*, including multibeam data collection at depths > 300 m during transits between islands and at Anatahan, were conducted during limited periods in daylight hours and almost continuously at night to complement and overlap the *AHI* shallow data and to fill in gaps in an overall synthesis of data sets from several organizations.

Data Acquisition

Since 2004, the R/V *AHI* and *Hi`ialakai* have been the exclusive platforms for CRED multibeam mapping missions. Real-time data acquisition and processing often occurred concurrently and involved several processing steps and software packages. For more details, see the "Documentation" section of the PIBHMC Web site at http://www.soest.hawaii.edu/pibhmc/pibhmc_documentation.htm.

Multibeam data were collected with an ISS-2000 collection module from the Science Applications International Corporation (SAIC, McLean, Va.). Sensors were interfaced to the system through a software module called a data transaction center (DTC), which was used to set sensor settings, calibration parameters, quality-control parameters, input formats, and output file formats. Each of the DTC modules stored data from its corresponding sensor in the appropriate file formats and assigned the appropriate names to each file. Most data were stored in ASCII text files, but the binary generic sensor format (GSF; Ferguson and Chayes 1995; SAIC 2008) was used specifically for multibeam data. Each unique filename was based on the sensor collecting the data, collection date, and a sequential extension.

A benefit of the ISS-2000 integrated survey system is that all sonar correctors are applied in real time during data collection. All data were displayed in real time for quality control and guidance of survey progress. Each GSF echosounder file not only stored all information necessary to provide the depth for each beam but also contained a permanent record of every action taken during data collection and processing.

Data Processing

Collected data were corrected for ship motion, navigation, sound velocity, and predicted tides, if selected. Predicted tidal correctors were applied, using data from the NOAA Center for Operational Oceanographic Products and Services, to multibeam data during collection to minimize apparent errors that may be caused by tide offsets or other system problems. Many of these corrections can be reapplied or changed, if desired, using SAIC's survey analysis and area-based editor (SABER), a compatible data processing package. To the majority of multibeam bathymetric data collected, 4 processing steps were applied:

- Application of alternate sound velocity profiles to a limited number of multibeam swath files
- Application of corrected tides (if available and needed) to some or all multibeam swath files to replace the predicted tides applied in real-time during data collection
- Visual editing of individual multibeam swath data files in GSF
- Assembly of all data in a given area within a Pure File Magic (PFM) grid and visual editing using an area-based editor

After edits were made to a PFM grid, data were downloaded back to their GSF files, where flags were set to indicate edits. These processed GSF files were used for data synthesis work at the PIBHMC and were documented with metadata; GSF files with metadata were sent to the NOAA National Geophysical Data Center on a cruise-by-cruise basis.

After grid editing was completed, a PFM grid was exported to ASCII or other grid formats, or the original GSF files were regridded and output to these formats. Standard grids were performed at 5 m, 10 m, or 60 m, depending upon the depth range and resolution required for a specific map. In general, 60-m grids are used for regional views that include deepwater areas, while 5- and 10-m grids are used for high-resolution maps of shallow areas. GSF, ASCII, or other grid files were then transferred to other data processing and visualization packages, including ArcGIS (Environmental Systems Research Institute Inc. [ESRI], Redlands, Calif.) and the following open-source systems:

MBSystem: an open-source software package for the processing and display of bathymetry and backscatter imagery data derived from multibeam, interferometry, and sidescan sonars (http://www.mbari.org/data/mbsystem/).

Generic Mapping Tools: an open-source collection of tools for manipulating XY and XYZ data sets and producing gridded data in a variety of formats and visualizations in the encapsulated postscript format (http://www.soest.hawaii.edu/gmt/).

Backscatter data were collected and stored as part of standard GSF files and processed at the PIBHMC using software developed at the University of Hawai`i by the Hawai`i Mapping Research Group to process seafloor acoustic imagery files. This software has been modified to accept GSF backscatter data from the Reson 8101 ER and Kongsberg EM 300 and EM 3002D multibeam sonars. The following steps were included in backscatter data processing: file conversion, splitting, speckle and microstrip removal, angle-varying gain correction, and assignment of data to a grayscale color map. For a complete discussion of these processing steps, see the "Multibeam Backscatter Processing Overview" document on the PIBHMC Web site (http://www.soest.hawaii.edu/pibhmc/pibhmc_documentation.htm).

Several issues regarding backscatter data and processing affect the subsequent products, such as hard–soft substrate and backscatter maps. A number of different parameters contribute to backscatter intensity values, including sonar frequency and settings (e.g., power, range, and gain), operational procedures (e.g., speed and consistent survey direction), and seafloor characteristics (e.g., slope, roughness, and hardness). Thus, although backscatter intensity is a valuable tool for investigating seafloor characteristics (e.g., roughness and hardness), backscatter values reflect a combination of parameters, and distinguishing the effect of one parameter from others may not be possible.

The most important factors that have caused noticeable artifacts or differences in data sets are sonar frequency, settings, slope, and survey procedures. Sonar frequency is inversely related to wavelength, and different wavelengths penetrate and interact with substrate in different manners (e.g., low frequencies penetrate more than high frequencies). Thus, trying to merge backscatter data sets from 2 different frequencies (30 kHz and 240 kHz) is not advisable, particularly for soft substrates. The second major issue is that sonar settings, particularly on the Reson 8101 ER multibeam, were changed in some very steep nearshore areas where operators were trying to map in depths near the maximum range of that sonar. Often, the deepest Reson 8101 ER swath shows very different characteristics than shallower ones, because of erratic sonar settings or steep slopes. Therefore, for some islands, the outer swath was discarded or the backscatter data was clipped at a uniform depth to improve the quality of hard–soft maps. Finally, survey procedures also greatly influence the quality of multibeam backscatter data. The MARAMP 2003 surveys, which were some of the first done by CRED while standard survey procedures were still under development, were often performed at higher speeds than surveys in later years. Although, to optimize backscatter data quality, it is desirable to run straight lines at uniform depths, it is almost impossible to run straight-line surveys around the small, steep islands of the CNMI. Survey swaths, then, were mostly "doughnuts" with nearshore beams looking upslope and offshore beams looking downslope—not an ideal scenario for producing high-quality backscatter data.

Bathymetry and Backscatter Derivatives

Additional analyses of the bathymetric grids provide slope, rugosity, and BPI parameters that are useful for determining the character of the seafloor and associated benthic habitats (Fig. 2.2.2b):

- **Slope:** Cell values reflect the maximum rate of change (°) in elevation between neighboring cells. Slope was derived from multibeam bathymetry using the ArcGIS Spatial Analyst tool (version 9.3).

- **Rugosity:** Cell values reflect the ratio of surface area to planimetric area for the area contained within a cell's 9-cell neighborhood. They provide indices of topographic roughness and convolutedness (Jenness 2004). Distributions of fishes and other mobile organisms are often found to positively correlate with increased complexity of the seafloor. Investigations are underway to determine which of the many methods available for quantifying benthic complexity best correlate with fish distributions in Pacific coral reef ecosystems. Results using the method described in the Jenness (2002) ArcView extension are provided as a standard and well-documented interim product. ArcGIS 9.3 and the Benthic Terrain Modeler, downloadable from the NOAA Coastal Services Center (http://www.csc.noaa.gov/products/btm/), were the tools used to derive rugosity.

- **BPI:** Bathymetric position index is a second order derivative of bathymetry that evaluates differences between the elevation of a focal point and the mean elevation of the surrounding cells within a user-defined annulus or circle. A negative value represents a cell that is lower than its neighboring cells (depressions), and a positive value represents a cell that is higher than its neighboring cells (crests). The larger the numbers, the more prominent the features on the seafloor that differ greatly from surrounding areas. Flat areas or areas with a constant slope produce values near zero (Lundblad et al. 2006). ArcGIS and the Benthic Terrain Modeler were the tools used to derive BPI.

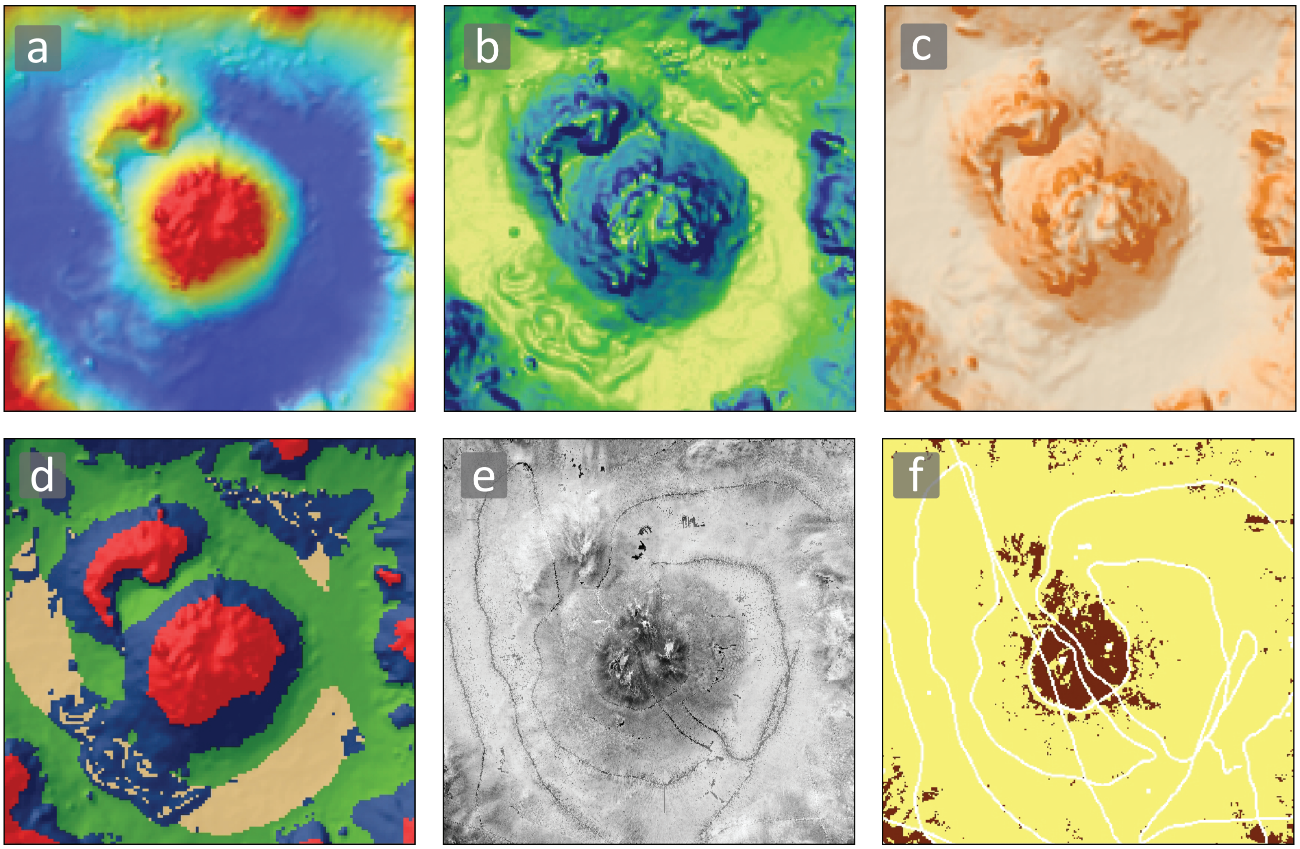


Figure 2.2.2b. Benthic habitat mapping data provide valuable information about seafloor characteristics, as seen, for example, in the above images of the caldera of Maug: (*a*) multibeam bathymetry, (*b*) slope, (*c*) rugosity, (*d*) BPI zone, (*e*) multibeam backscatter, and (*f*) hard and soft substrates.

All of the previous analyses are performed on 5- or 10-m grids of bathymetric data, clipped to 400-m or 800-m depths, respectively. These cutoff depths were chosen to ensure that grid cell size has approximately the same resolution as the average footprint of the original swath data over a range of depths.

Multibeam (bathymetry and backscatter) and optical-validation data were used to derive substrate maps in the following manner: Cell values reflect whether the seafloor is hard bottom (solid rock, boulders, and rubble) or soft bottom (sand and mud), based on an unsupervised classification run in ENVI software (version 4.3, ITT Visual Information Solutions, Boulder, Colo.). These classifications were based on backscatter, bathymetry, and acoustic derivatives. Substrate classification (hard bottom versus soft bottom) was derived from a combination of backscatter imagery and bathymetric variance and the results were then compared to optical-validation data using ENVI software, rather than first using optical data to supervise or instruct the ENVI software in a "supervised" classification process. Weiss et al. (2008) documented the development of the PIBHMC methods for unsupervised hard–soft substrate classification in a paper available on the center's Web site.

2.2.3 Combined Bathymetry Maps

For 4 islands, additional bathymetry data were available to complement the multibeam data collected by CRED, specifically providing more complete coverage in shallow areas. These bathymetry data were either collected by lidar or derived from IKONOS satellite imagery. This section explains how these 2 types of data were acquired and how each type was combined in different ways with the multibeam data collected by CRED to create integrated bathymetry maps.

Lidar and Multibeam Data

The Naval Oceanographic Office of the U.S. Navy conducted bathymetric surveys at priority areas around the southern islands of the Mariana Archipelago between January 8 and March 20, 2001 (Naval Oceanographic Office 2004). The primary sensors used for these surveys from the shoreline to the lidar extinction depth (~ 20–40 m in these areas) were a scanning hydrographic operational airborne lidar survey (SHOALS) system on a DeHaviland Twin Otter aircraft.

Surveys were conducted in 5 primary areas:

- Guam: inner and outer Apra Harbor, Agat Bay (tide corrected)
- Guam: coastal areas specified by the U.S. Geological Survey, U.S. Fish and Wildlife Service, and U.S. Army Corp of Engineers (no tide corrections)
- Saipan: offshore and inshore anchorages and harbor
- Tinian: northern training area, southern coastline and anchorage, Tinian Harbor
- Farallon de Medinilla

In areas beyond the lidar extinction depth, bathymetric data were also collected aboard the USNS *Sumner*, using this ship's Simrad EM1002 multibeam echosounder.

For the Guam combined data set, areas too deep for lidar were surveyed using single-beam sonar. For the Tinian, Saipan, and Farallon de Medinilla combined data sets, areas too deep for lidar were surveyed using multibeam sonar.

Estimated Depths from IKONOS Satellite Imagery

Satellite remote-sensing imagery, primarily from IKONOS satellites, has been purchased by the CRCP for almost all of the U.S. Pacific islands. This imagery has been used to create benthic habitat maps using visual interpretation methods and as a visual base layer for many maps. The use of satellite remote-sensing data (e.g., IKONOS, QuickBird) to derive "estimated depths" has been a topic of research since the publication in 1978 of an early paper by David R. Lyzenga (Lyzenga 1978). A recent study supported by CRED (Hochberg et al. 2007) compared a number of different methods and demonstrated that the most accurate method was simple, empirical multiple linear regression against known depths (Lyzenga 1985). In general, derivation of estimated depths is most successful in relatively shallow water (< 20 m) and where overlapping depth data from multibeam or lidar sources are available for verification.

CRED has supported a project to derive estimated depths and perform error analyses using the Lyzenga (1985) method in areas where (1) the available IKONOS imagery is of high quality, (2) there are shallow banks (as opposed to steep flanks) where this technique might successfully be used, and (3) enough overlapping multibeam or lidar data exist to calibrate each image. In the Mariana Archipelago, acceptable estimated depths wre derived around Tinian. Other areas under investigation for estimated depth derivation include Saipan and Maug. This method allows data gaps to be filled, particularly in nearshore areas where neither multibeam nor lidar depth data are available.

Data Processing

When additional bathymetric data were available for areas where CRED was unable to obtain multibeam data, these data were combined with the multibeam data collected by CRED to produce an integrated depth grid and map. Once an integrated depth map was generated, it then was used to derive slope, rugosity, and BPI estimates.

One test of whether estimated depths accurately depict the seafloor is to evaluate adjacent rugosity values, comparing areas of estimated depths with multibeam or lidar data. If estimated depths consistently show higher rugosity than measured depths, which would indicate higher noise in estimated depths, then rugosity derived from those estimated depths should not be used for interpretation. Also, it is not possible to derive hard–soft maps from these integrated depth maps because the hard–soft product is dependent upon the use of multibeam sonar backscatter data.

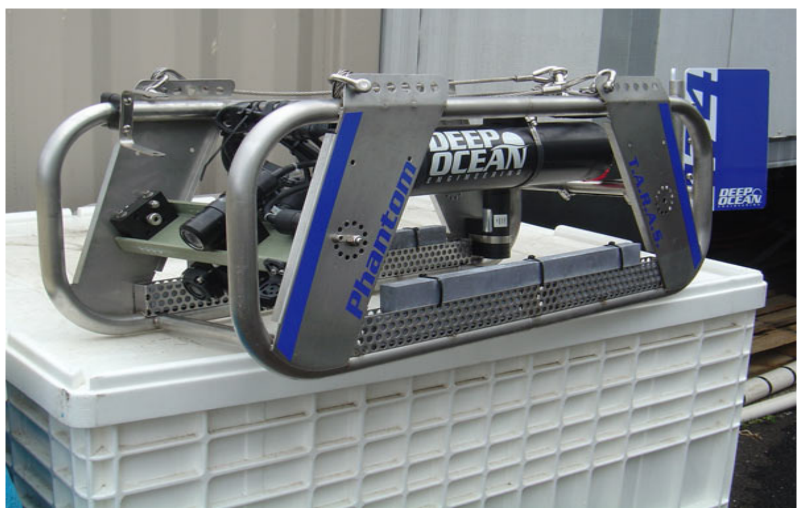
2.2.4 Optical Validation

Observations from towed-diver and TOAD surveys provide information about the seabed that is complementary to the acoustic products. Although acoustic techniques are invaluable in providing seafloor maps with high spatial coverage, acoustic signals can be influenced by factors other than the acoustic character of the seabed. Therefore, direct observations from towed-diver or TOAD surveys are an important tool for validating the seabed characteristics predicted by acoustic maps.

TOAD Surveys

CRED has used camera sleds to collect optical seafloor characterization data since 2001. The first TOAD configuration, used in the Mariana Archipelago in 2003, integrated a digital still camera, an underwater video camera, lights, a sonar altimeter, pressure transducer, and parallel scaling lasers on a Guideline Instruments Ltd. (Smith Falls, Ontario, Canada) MiniBAT 8820 tow body (Fig 2.2.3a). Typically, the TOAD is maintained at ~ 1–5 m above the seafloor but may frequently fly higher because of operational constraints. The TOAD operator entered the estimated layback distance into the MiniBAT software, which integrated the device with ship position to provide estimated positions of the tow body along survey tracks. Estimated positional accuracies using this method were on the order of 50 m. Various operational scenarios were tested, and, after several cruises, the technique of towing the TOAD at speeds of 0.5–1 kt in a drift mode was most effective and presented the least overall risk to both the tow body and shipboard personnel operating the winch, particularly over high-relief terrain.

Figure 2.2.3a. TOAD configuration used in 2004 in the Mariana Archipelago to collect optical seafloor characterization data. These devices combine a digital still camera, underwater video camera, lights, and other equipment.



For the completion of the project to collect additional optical data at the Garapan Anchorage in 2004, camera sleds that could be deployed from small boats were required. Two new sleds, using a modified Phantom ROV frame were designed and built by Deep Ocean Engineering of San Leandro, Calif. These TOADs were equipped with a Deep Sea Power & Light Multi-SeaCam 2060 low-light color video camera, two 500-watt Deep Sea Power & Light model 710-0400601 underwater lights, a Tritech International PA200-20 sonar altimeter to detect the height of the camera above the seafloor, a Deep Sea Power & Light SeaLaser 100 parallel laser-pair for scaling, a compass for determining sled headings, and a depth (pressure) sensor. These camera sleds were attached to a control console via 200 m of 1.27-cm diameter umbilical cable. A video display monitor mounted on the control console was used to monitor the position of a sled relative to the seafloor. Video data were recorded to digital video cassette using a video recorder also mounted on the control console. Hypack Max (version 2.12A, Hypack Inc., Middletown, Conn.) hydrographic survey software was used to record global positioning system (GPS) data, depth, length of umbilical cable in the water, and camera-sled information (altitude, heading, etc.), which provide ship and camera-sled positions for the duration of individual TOAD surveys.

TOAD operations were conducted in 2003 around the following islands and banks: Guam, Santa Rose Reef, Galvez Bank, 11-mile Reef, Rota, Aguijan, Saipan, Anatahan, Sarigan, Guguan, Alamagan, Pagan, Agrihan, Asuncion, Maug, Farallon de Pajaros, Esmeralda Bank, Zealandia Bank, Supply Reef, Arakane Reef, Pathfinder Reef, and Stingray Shoal. In 2004, an additional 123 linear km of optical data were collected in the Garapan Anchorage off Saipan.

Seafloor videography collected during TOAD deployments were analyzed using a series of 5 small, fixed circles extending in a straight horizontal line marked on a video monitor screen. The types of substrate and living cover that fell within these circles were identified at 20-m or 30-s increments along a camera's trackline. Some video frames from TOAD footage were not analyzed because of poor image quality.

Types of substrate included sand, rock, and rubble, and types of living cover included macroalgae, crustose coralline red algae, hard (scleractinian) coral, and other benthic fauna. Other biologically relevant observations were made as well. The full listing of benthic habitat classifications is shown in Table 2.2.4a. TOAD habitat classifications are incorporated in attribute tables associated with ArcView shapefiles that show the location of TOAD tracks over the seafloor. The TOAD data presented in this report are percentages of sand cover, live-hard-coral cover, and macroalgal cover.

Table 2.2.4a. Benthic habitat classifications used in analysis of video from TOAD surveys.

Zones	Classes	Zones	Classes
Depression	Narrow depression	**Slopes**	Lateral midslope depression
	Broad depression with open bottom		Open slope
	Local crest in depression		Lateral midslope crest
System	Basalt island		Steep slope
	Sea stack	**Coral (Growth) Morphology**	Massive
	Carbonate island		Platelike
	Closed atoll		Encrusting
	Open atoll		Branching
	Submerged bank/reef		Columnar
	Continental reef		Free living
Living Cover	Scleractinian corals	**Holes**	No cavities
	Non-scleractinian corals		Few small cavities
	Coralline algae		Many small cavities
	Corals or coralline algae		Few large cavities
	Macroalgae		Many large cavities
	Turf algae		Few small and large cavities
	Unclassified algae		Many small and large cavities
	Emergent vegetation		Many small and few large cavities
	Giant clams	**Substrate**	Unconsolidated (mud)
	Other Non-mobile invertebrates		Unconsolidated (sand)
Crests	Depression on crest		Hard bottom (rubble)
	Narrow crest		Hard bottom (boulder)
Flats	Local depression on flat		Hard bottom (rock)
	Broad flat		Hard bottom (man-made structure)
	Shelf		
	Local crest on flat		

Towed-diver Surveys

Data that characterizes the benthic habitats around the Mariana Archipelago in depths of 3–30 m were collected during towed-diver surveys as part of MARAMP 2003, 2005 and 2007. These benthic habitat characterizations provided background for analyses of biological data collected during towed-diver surveys and for validation (ground truthing) of habitat maps created with acoustic or satellite-derived information. A brief overview of towed-diver surveys and details on the benthic habitat categories used to make habitat characterization maps are presented in this section. The data collected during towed-diver benthic surveys are discussed fully in Section 2.4: "Reef Surveys: Corals, Algae, Macroinvertebrates, Fishes, and Substrates."

These survey methods involved towing 2 divers ~ 60 m behind a small boat, with each diver maneuvering to maintain their position ~ 1 m above the seafloor. A typical survey covered 1.5–2.5 linear km of habitat, targeted specific isobaths, and lasted 50 min. Surveys were divided into 10 segments, each 5-min and ~ 200 m in length, during which towed divers recorded visual estimates of habitat complexity and benthic substrate cover within a 10-m swath (5 m on either side of the tow line).

In addition to visual estimates of benthic cover, photographs of the benthos were taken with a downward-looking digital still camera at 15-s intervals. Also, an oblique digital video camera recorded continuous observations of the seafloor. The photos and video imagery collected during MARAMP surveys have been archived for future analyses.

Classification of habitat complexity involves a subjective assessment of topographical diversity and complexity over a large scale (~ 2000 m^2) based on 6 categories: low, medium-low, medium, medium-high, high, and very high. For example, a sandy bottom with scattered macroalgae has low habitat complexity. In contrast, a shallow reef with numerous growth forms of corals and a 3-D structure providing shelter for reef fishes of various size categories has a complexity rating medium-high to very high (see Fig. 2.4.4a in Section 2.4.4: "Benthic Habitat Complexity and Substrates" for visual examples of each complexity category).

Benthic habitat cover was estimated for 2 kinds of substrate: live hard coral and sand cover. The category of live hard coral cover included colonies or portions of colonies of live pigmented tissue. The sand cover category included unconsolidated sediment, ranging in texture and size from fine to course. Sand cover origins were both inorganic (eroded rock) and organic (eroded fragments of calcareous organisms).

Data from towed-diver observations and analysis of TOAD video footage, acquired by the very different methods described earlier, vary in terms of scale and the influence of observer subjectivity. Data also can vary spatially because towed divers and TOAD deployments survey different depth profiles. As long as these important differences are borne in mind, both sets of data provide valuable information about the nature of a seabed, and they are, therefore, presented together in habitat characterization maps that combine sand cover, habitat complexity, and live hard coral cover.

2.3 Oceanography and Water Quality

To assess the oceanographic and water-quality parameters influencing the coral reef ecosystems in the Mariana Archipelago, CRED collected and integrated 5 key data streams: (1) deepwater oceanographic surveys characterizing prevailing water properties and ocean currents around the islands and reefs in the Mariana Archipelago; (2) intensive, closely spaced, nearshore oceanographic and water-quality surveys conducted concurrently with biological surveys; (3) an array of surface and subsurface moored instruments providing continuous, high-resolution time-series observations; (4) satellite remote-sensing products providing spatial time-series observations of key oceanographic properties, such as sea-surface temperature, sea-surface height, surface winds, chlorophyll-a (Chl-a), and other derived products; and (5) numerical models, such as NOAA Wave Watch III, providing spatial and temporal estimates of various oceanographic parameters.

2.3.1 Operational Background and Survey Design

CRED has utilized a diverse suite of data collection methodologies to monitor and assess local and regional oceanographic and water-quality conditions, including in situ telemetered surface and subsurface moored instruments, shipboard and nearshore spatial hydrographic surveys performed during research cruises, and deployment of ecological acoustic recorder (EAR) instruments. Oceanographic equipment and instrument specifications are provided later in this report. Shipboard surveys in the Mariana Archipelago were conducted from NOAA research vessels, and nearshore surveys and instrument deployments and retrievals were accomplished by small boats deployed from these research vessels.

Monitoring sites were selected to characterize the prevailing climatic and oceanographic conditions by spatially and temporally quantifying key physical and biogeochemical forcing mechanisms pertinent to biological processes (e.g., temperature, salinity, turbidity, currents, wave energy, ultraviolet [UV] radiation, nutrients, Chl-*a*, dissolved oxygen, dissolved inorganic carbon) over seasonal, interannual, and decadal time scales. With this work, CRED is generating long-term time series of baseline observations of environmental conditions that influence reef ecosystems. These time series are essential for understanding and predicting the ecological impacts of global climate change and land-based sources of pollution.

2.3.2 Shipboard Surveys

Shipboard deepwater (500-m) conductivity, temperature, and depth (or pressure, CTD) casts with simultaneous water sample collection were conducted to determine prevailing water property profiles surrounding the islands in the Mariana Archipelago. These deepwater casts provide high-resolution vertical profiles of conductivity (salinity), temperature, dissolved oxygen, and Chl-*a* concentration versus depth. In addition, shipboard acoustic Doppler current profiler (ADCP) transects were conducted in deepwater regions around each island to examine the horizontal and vertical structure of the prevailing ocean currents (Lumpkin and Pazos 2005). CTD and ADCP data are critical information that aid in the assessment of offshore water mass properties and essential for contextualizing and interpreting nearshore oceanographic information.

Deepwater CTD Casts

A Sea-Bird Electronics Inc. (Bellevue, Wash.) SBE 911*plus* CTD (accuracy of 0.003 S m^{-1}, 0.001 °C, 0.015% feet of seawater) with an SBE 43 dissolved oxygen sensor (accuracy of 2% saturation) and a WET Labs (Philomath, Ore.) *ECO* FLNTU combined fluorescence and turbidity sensor (accuracy of 0.01 µg L^{-1}, 0.01 NTU) was used to collect vertical profiles of water properties from the surface to a depth of 500 m in offshore environments around each island or reef surveyed (Fig. 2.3.2a). In addition, a rosette with multiple 10-L Niskin bottles was used to collect water samples for Chl-*a* and nutrient analyses at selected depths. Data from deepwater CTD casts are presented in Chapter 3: "Archipelagic Comparisons," Section 3.3: "Oceanography and Water Quality."

Figure 2.3.2a. Shipboard deepwater CTD casts are conducted with an SBE 911*plus* profiler, which is outfitted with a rosette of Niskin water bottles for concurrent water sampling.

Shipboard ADCPs

Transects of ocean current velocity profiles were collected using shipboard ADCPs during MARAMP 2003, 2005, and 2007. During each research cruise, surveys were conducted using a hull-mounted 75-kHz Teledyne RD Instruments Inc. (Poway, Calif.) Ocean Surveyor. This system was configured with an 8-m pulse length that typically collects current profiles in 16-m depth bins over the range of ~ 25–600 m averaged into 15-min ensembles. The actual depth range depended on the density and abundance of scattering material in the water column. Additional data were generally collected continuously while vessels were underway. Although ADCP information is not presented in this report, data are served by NOAA's National Oceanographic Data Center and available for download at http://www.nodc.noaa.gov.

2.3.3 Nearshore Spatial Surveys

Closely spaced, nearshore CTD surveys were conducted throughout the shallow-water environments around each of the islands, banks, and reefs surveyed during all of the MARAMP cruises. The distance between adjacent casts ranged from 0.25 to 2.0 km, depending on the size of the area sampled with each cast typically conducted to a depth of ~ 30 m. These surveys characterize the spatial structure of the physical and chemical properties of the ocean environment influencing the living coral reef resources observed during Rapid Ecological Assessment (REA) and towed-diver surveys. To examine nearshore water quality, water samples were collected at a subset of the shallow-water CTD sites.

Shallow-water CTD Casts

Shallow-water CTD casts were conducted using an SBE 19*plus* Seacat Profiler CTD (accuracy of 0.005 S m^{-1}, 0.0002 °C, 0.1% feet of seawater), providing vertical profiles of conductivity and temperature versus depth. Beam transmission data were collected concurrently using a WET Labs C-Star transmissometer. CTD profiles were collected by hand-lowering the CTD instrument (Fig. 2.3.3a) from a small boat at a descent rate of ~ 0.5–0.75 m s^{-1} to a maximum depth of 30 m. Shallow-water CTD observations around each island are presented as vertical cross-sectional plots, which were generated using Matlab software from The MathWorks Inc., Natick, Mass. Subsets of this data representing the same oceanographic parameters at a depth of 10 m are presented to further illustrate their spatial structure around each island. Results for some casts and water samples are not presented in this report because either the data were redundant or erroneous or no data were produced.

Figure 2.3.3a. Shallow-water CTD casts are conducted with an SBE 19*plus*, held by Kevin Wong, for nearshore profiling of salinity, temperature, and pressure-based depth. *NOAA photo*

Seawater Laboratory Analyses

Water sampling was conducted at a subset of the shallow-water and deepwater CTD sites. During shallow-water CTD casts, water samples were collected by lowering a daisy chain (or linked series) of 1.75- and 5-L Niskin bottles, triggered with a trip weight so that separate water samples were collected at depths of ~ 1, 10, 20 and 30 m. These water samples were preserved for laboratory analyses of water quality, including levels of Chl-*a*, nitrates, nitrites, phosphates, silicates, total nitrogen, and dissolved inorganic carbon (DIC). Water samples taken for Chl-*a* analysis were processed by Paul Bienfang, PhD, of Analytical Services Inc., Honolulu. Water samples taken for analyses of nutrients and DIC were processed at the NOAA Pacific Marine Environmental Laboratory in the nutrient laboratory of Calvin Mordy, PhD, and in the carbonate chemistry laboratory of Richard Feely, PhD.

2.3.4 Surface Moorings

As key components of the NOAA CREIOS, Coral Reef Early Warning System (CREWS) and sea-surface temperature (SST) buoys were moored in shallow-water environments around many U.S. Pacific islands. The types of instruments deployed at each island or offshore bank are provided in Figure 2.3.6a. SST and CREWS buoys provide near real-time observations of oceanographic conditions influencing coral reef ecosystem processes to managers, stakeholders, and the public. These surface observations are transmitted via satellite for daily dissemination at the CRED website (http://www.pifsc.noaa.gov/cred/oceanography.php). In addition to this telemetered data, buoys store SST observations internally, and CRED downloaded this data from buoys when they were retrieved during MARAMP cruises. Data from the SST and CREWS buoys installed in the Mariana Archipelago, as well as the locations and timelines of these buoy deployments, are presented in the "Oceanography and Water Quality: Time-series Observations" sections of the relevant island chapters of this report.

Coral Reef Early Warning System Buoys

CREWS buoys telemeter in situ observations of atmospheric and oceanographic parameters influencing reef conditions (Fig. 2.3.4a). For a single location at Saipan, a series of CREWS buoys deployed between August 2003 and May 2007 provided near real-time, high-resolution SST and surface conductivity data at a depth of 1 m (SBE 37 MicroCAT recorder, accuracy of 0.0028ºC, 0.0003 S m^{-1}), air temperature (WS425 sensor, accuracy of 0.38ºC, R.M. Young Company, Traverse City, Mich.), barometric pressure (Heise DXD transducer, accuracy of 0.02% feet of seawater, Ashcroft Inc., Stratford, Conn.), wind speed and wind direction (Vaisala sensor, accuracy of 0.135 m s^{-1} in speed and 2° in direction, Helsinki, Finland), photosynthetically active radiation and 3 bands of ultraviolet radiation (305, 330, and 380 nm) measured nominally 2 m above the surface of the water and nominally 1 m below the surface.

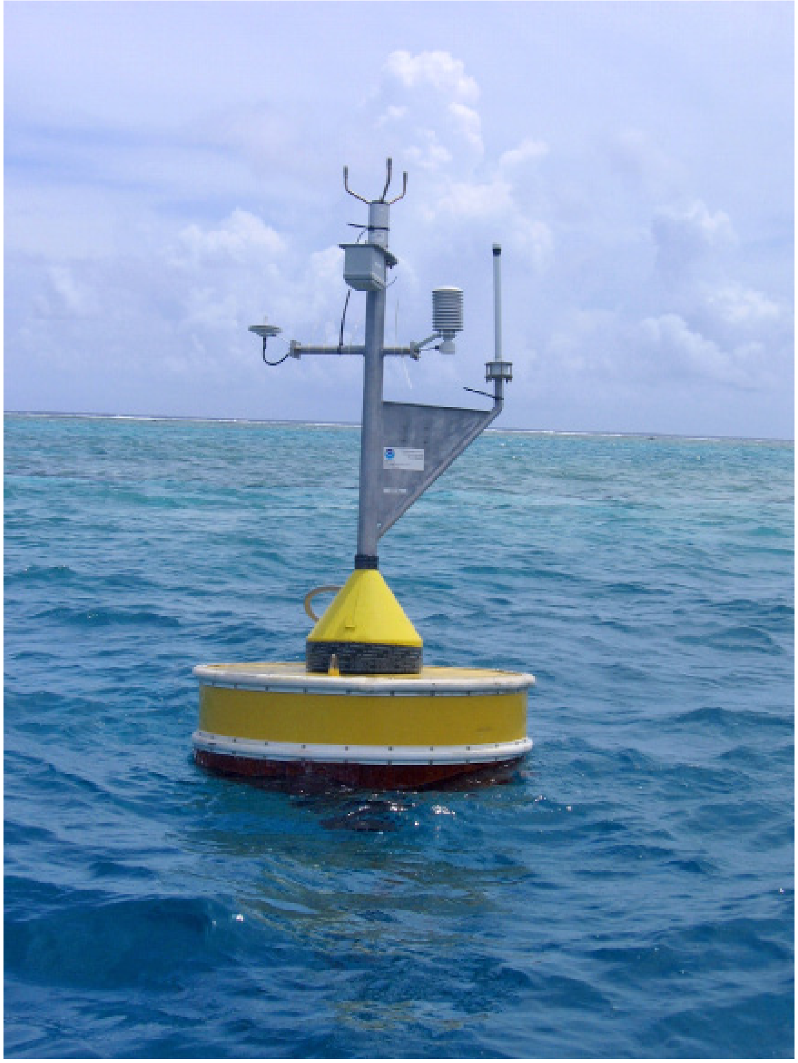


Figure 2.3.4a. Coral Reef Early Warning (CREWS) buoys relay oceanographic and meteorological data via satellite telemetry.

Sea-surface Temperature Buoys

SST buoys telemeter in situ observations of high-resolution SST in near real time. SST buoys were deployed beginning in September 2003 at Guam, Pagan, and Maug and beginning in May 2007 at Rota and Saipan. Data have been recorded internally and transmitted via satellite at 30-min intervals. There are 2 types of SST buoys: an Ocean Trek Research (Wasilla, Alaska) OTR-200 solar rechargeable buoy and a battery-powered Sound Ocean Systems Inc. (Redmond, Wash.) Model SST-001 (Figs. 2.3.4b and c).

Figure 2.3.4b. An Ocean Trek Research OTR 200 sea-surface temperature buoy at Pagan. *NOAA photo*

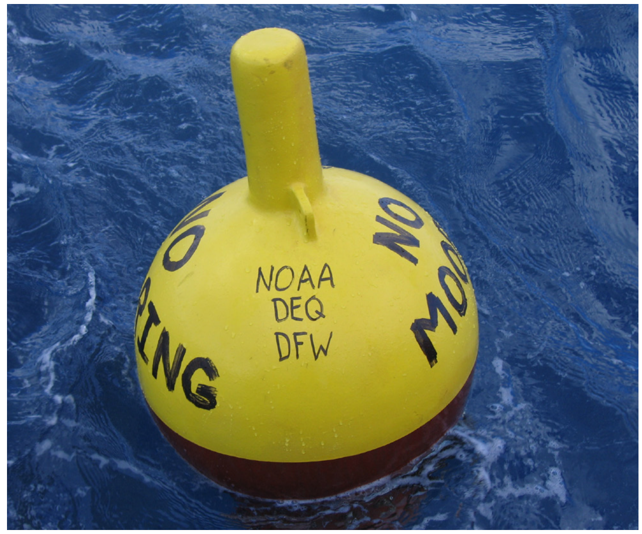


Figure 2.3.4c. A Sound Ocean Systems Inc. Model SST-001 sea-surface temperature buoy off Saipan. *NOAA photo*

2.3.5 Subsurface Moorings

Ocean data platforms (ODPs), wave-and-tide recorders (WTRs), and subsurface temperature recorders (STRs) are the types of subsurface moorings that were deployed at select locations around the Mariana Archipelago and configured to regularly record important oceanographic and ecological parameters that influence coral reef conditions. These moored instruments were recovered on a periodic basis and replaced with refurbished units to maintain a continuous time series of data at each location. Data from these STRs, as well as the locations and timelines of their deployments, are presented in the “Oceanography and Water Quality: Time-series Observations” sections of the relevant island chapters of this report. Similar information, as noted later in this section, is provided for the ODP and WTR deployments. The types of instruments deployed at each island or offshore bank are provided on a map in Figure 2.3.6a.

Ocean Data Platforms

ODPs recorded directional current profiles and wave spectra and high-resolution ocean temperature and salinity (Fig. 2.3.5a). ODPs, equipped with a 1000-kHz SonTek ADP, which is an acoustic current Doppler profiler (ADCP) from SonTek/YSI (San Diego, Calif., accuracy of 0.005 m s^{-1}, 0.1% feet of seawater) and an SBE 37 MicroCAT conductivity and temperature recorder, were deployed at Santa Rosa Reef in 20 m of water from September 2003 to September 2005 and from October 2005 to May 2007.

Current data from the ADCP were sampled for 7 min every 2 h, waves were burst sampled for 20 min every 4 h, and temperature and salinity data were sampled at 30-min intervals. Data were internally recorded and retrieved from platforms during subsequent MARAMP cruises. Data from the ODP mooring site at Santa Rosa Reef are presented in Chapter 4: “Guam and Adjacent Reefs and Banks,” Section 4.10.4: “Oceanography and Water Quality.”

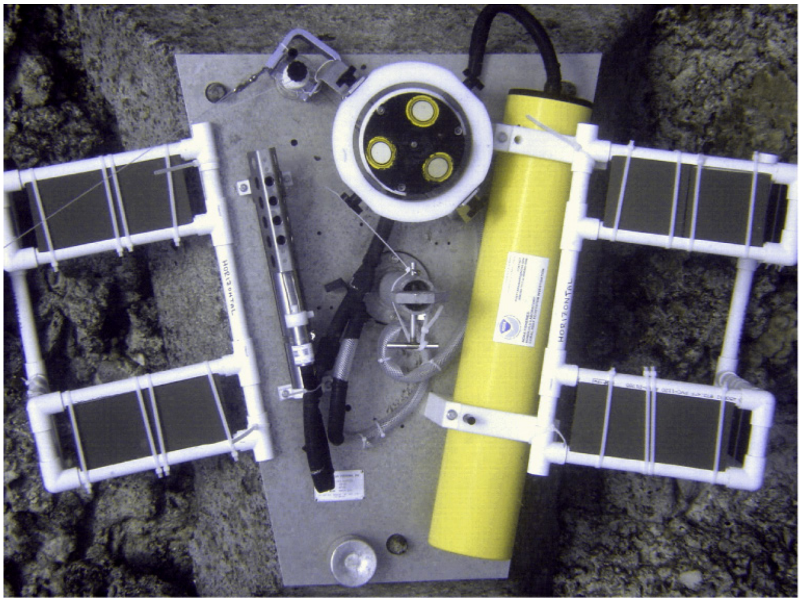


Figure 2.3.5a. Ocean data platforms (ODP) record several types of data: current profiles, wave spectra, and temperature and salinity values.

Wave-and-tide Recorders

WTRs consist of an SBE 26*plus* Seagauge wave-and-tide recorder (accuracy of 0.01% feet of seawater) that registers observations of high-resolution pressure (wave height and tides) and temperature variations. Beginning in September 2003, WTRs have been deployed at a depth of 27 m at Supply Reef and a depth of 25 m at Zealandia Bank. Data have been internally recorded with sample intervals of 15 min every 6 h. Data from the WTRs moored at Supply Reef and Zealandia Bank are presented in Chapter 18: "Reefs and Banks of the CNMI."

Subsurface Temperature Recorders

STRs consist of SBE 39 temperature recorders (accuracy of 0.002 °C) physically attached to reef structures to register observations of high-resolution temperature changes that potentially influence corals and other benthic biota. Unlike CREWS buoys, SST buoys, and satellite observations of SST, STRs record the actual temperatures at the depth to which they are deployed. These observations are particularly important during calm conditions conducive to coral bleaching. At these times, the water column is often well-stratified, meaning that many corals may not be subjected to the warm temperatures of the sea surface and, thus, are less likely to experience bleaching events. Beginning in September 2003, STRs have been deployed at depths of 2–32 m in a variety of locations and habitats throughout the coral reef ecosystems in the Mariana Archipleago, including locations around Guam and 13 islands and 2 banks of the CNMI, particularly habitats considered at high risk for coral bleaching.

2.3.6 Oceanographic Equipment Deployment in the Mariana Archipelago

Oceanographic instruments have been deployed across the Mariana Archipelago since 2003 (Fig. 2.3.6a). Data collected by these instruments—as well as the numbers, timelines, and locations of instrument deployments and retrievals—at each island or offshore bank are described in the "Oceanography and Water Quality: Time-series Observations" sections of each island chapter, in Chapter 4: "Guam and Adjacent Reefs and Banks," Section 4.10: "Reefs and Banks," and in Chapter 18: "Reefs and Banks of the CNMI."

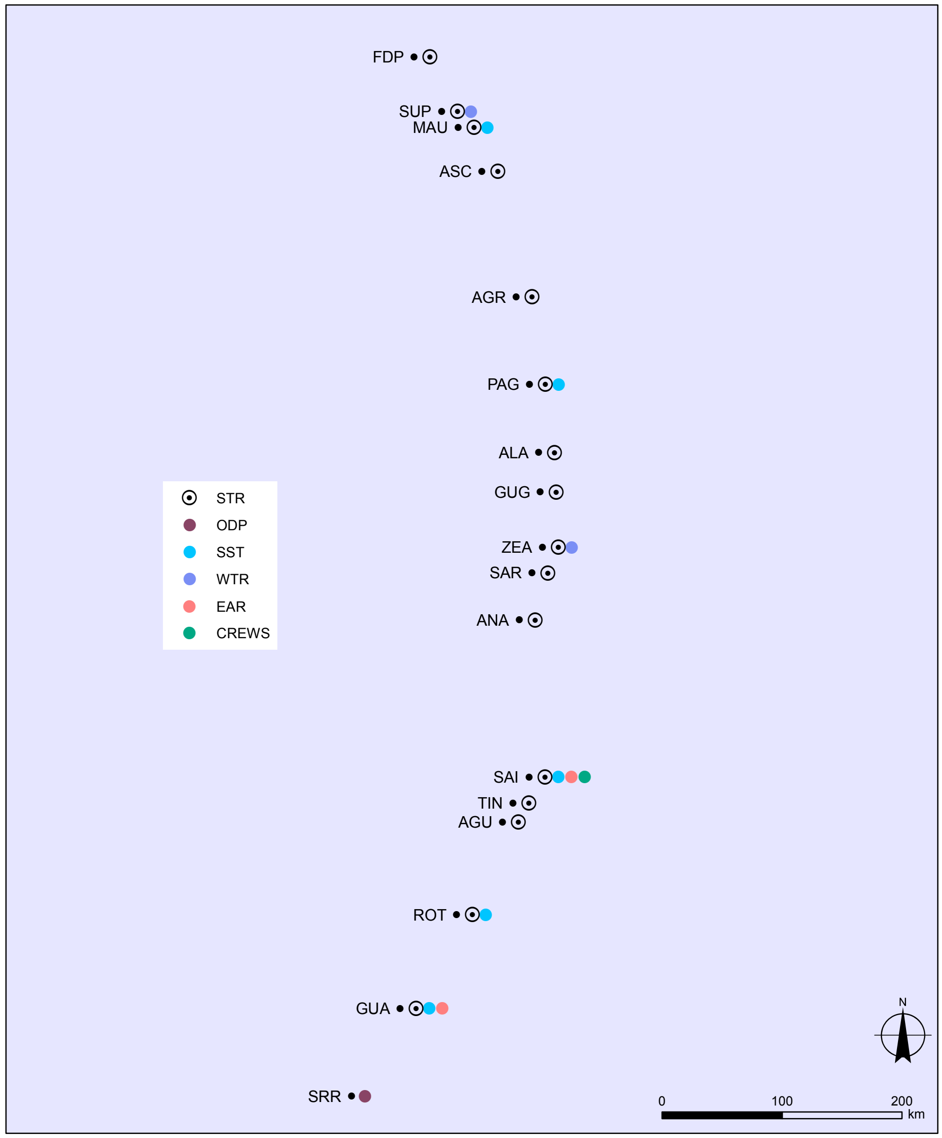


Figure 2.3.6a. Types of oceanographic and bioacoustic instruments and monitoring installation deployed at each island or bank in the Mariana Archipelago during MARAMP 2003, 2005, and 2007. Six types of moored instruments and one type of monitoring installation were deployed in this region during these survey years: autonomous reef monitoring structure (ARMS), Coral Reef Early Warning System (CREWS) buoy, ecological acoustic recorder (EAR), sea-surface temperature (SST) buoy, subsurface temperature recorder (STR), ocean data platform (ODP), and wave-and-tide recorder (WTR).

2.3.7 Satellite Remote Sensing and Ocean Modeling

Satellite Remote Sensing

All satellite-derived data products presented in this report are produced and distributed publicly by various government and private organizations. Brief summaries of data providers and any further analyses performed by CRED are outlined here:

1. NOAA advanced very high-resolution radiometer (AVHRR) Pathfinder 5.0 SST (Casey 2006)
   - http://www.nodc.noaa.gov/sog/pathfinder4km/
   - Infrared radiometer SST from NOAA polar orbiter satellites
   - grid resolution: 4 km
   - Climatology produced by the NOAA National Oceanographic Data Center (NODC) using the period of 1985–2001
   - Pathfinder 5.0 weekly data and climatology time-series plots are based on data extracted from 1° × 1° latitude-longitude boxes surrounding an area of interest
2. NASA Quick Scatterometer (QuikSCAT) SeaWinds
   - http://winds.jpl.nasa.gov/missions/quikscat/index.cfm

- Microwave scatterometer that measures near-surface wind speed and direction
- grid resolution: 0.25°
- Climatology produced by CRED and NODC for OceanEye project using the period of 2000–2003

3. NASA SeaWiFS Imager
   - http://oceancolor.gsfc.nasa.gov/SeaWiFS/
   - Measures bio-optical properties of the ocean, including a calculation of Chl-a levels
   - grid resolution: 9 km
   - Climatology produced by CRED and NODC for OceanEye project using the period of 1998–2003

Ocean Modeling: Bleaching Threshold

As early as 1997, the NOAA National Environmental Satellite, Data, and Information Service (NESDIS) began producing Web-accessible, satellite-derived, near-real-time SST products to monitor conditions conducive to coral bleaching from thermal stress around the globe. This activity evolved into a crucial part of the CRW program in 2000, and these products can be found at http://coralreefwatch.noaa.gov/satellite/index.html. SST data is provided at a resolution of 50 × 50 km (0.5° × 0.5°).

The bleaching threshold, developed by CRW, serves as a general indicator for coral bleaching and is defined as 1°C above the maximum monthly climatological SST value for a particular geographic area. It's important to note that satellite-derived SST represents the upper few millimeters of oceanographic temperatures within the region of an island, as opposed to site- or reef-specific temperatures.

CRED generated SST and wave-height time series around the islands of the Mariana Archipelago for the period between August 2003 and June 2007. Remotely sensed data (SST climatology and weekly satellite-derived [Pathfinder] SST) and modeled significant wave height derived from NOAA Wave Watch III were overlaid with CRED in situ observations from various locations around each island or reef in the Mariana Archipelago and with indicators for each area's bleaching threshold and MARAMP cruise dates. Time-series records produced for each island from in situ and telemetered data are presented in the "Oceanography and Water Quality: Time-series Observations" sections of island chapters.

Ocean Modeling: Wave Watch III

NOAA Wave Watch III is a third-generation, full-spectral ocean wind-wave model that provides historical and near real-time open-ocean, deepwater modeled spectral wave data (height, period, and direction). Three hourly forecasts of wave conditions, up to 144 h (6 d) in advance, are generated twice daily.

Wave Watch III solves the complexities of directional waves through the spectral action density balance equation for wavenumber-direction spectra. The implicit assumption of this equation is that properties of depth and current as well as the wave field itself vary on time and space scales that are much larger than the variation scales of a single wave. Another constraint is that the physical process parameters included in the model do not allow for assessment in conditions where waves are strongly limited in depth. These 2 basic assumptions imply that the model can generally by applied on spatial scales (grid increments) > 1–10 km and outside the surf zone (Tolman 1999, 2002; National Weather Service). For more information about Wave Watch III, go to http://polar.ncep.noaa.gov/waves/index2.shtml.

2.3.8 Monitoring of Bioacoustics

CRED monitors natural and man-made underwater ambient sounds, captured by a device known as the ecological acoustic recorder (EAR), to learn about the presence and activity of fishes, crustaceans, cetaceans (whales and dolphins), and other sound-producing marine life and about the frequency and occurrence of human activity in marine areas. EAR units have been deployed in 2 locations at Saipan, in Bahia Fanonchuluyan and near Puntan Laolao Kattan, and in 1 location at Guam northwest of Pati Point. The EAR is a digital, low-power passive acoustic system that records ambient sounds at frequencies up to 30 kHz on a programmable schedule. Equipped with a sound trigger, the EAR can also capture transient noises produced by cetaceans, passing vessels, or other acoustic events. EAR devices deployed over several months generate an amount of data far too great for manual analysis, so custom detection and classification software algorithms are used to automate the processing and analysis of data. EAR devices were deployed at Saipan (2 units) at Guam (1 unit) beginning in

May 2007. A time series of the data from the EARs installed at Saipan is provided in that island chapter. The locations and timelines of these EAR deployments are presented in the "Oceanography and Water Quality: Bioacoustic Observations" sections of the Guam and Saipan chapters.

2.4 Reef Surveys: Corals, Algae, Macroinvertebrates, Fishes, and Substrates

Information on the species composition (diversity), condition, abundance, and distribution of biological communities is vital to the effective management of coral reef resources. To provide resource managers with such information, CRED collects complementary data relating to 4 main ecological disciplines: corals, algae, other macroinvertebrates, and reef fishes (Table 2.4a). CRED acquires these integrated observations of reef-fish and benthic community structure primarily using Rapid Ecological Assessment (REA) surveys and towed-diver surveys.

During MARAMP 2003, 2005, and 2007, fine-scale REA surveys were conducted at specific reef sites (~ 300 m^2 per site), while broad-scale towed-diver surveys (~ 15,000–25,000 m^2 per survey) were performed around the islands and reefs of Guam and the CNMI. Analyses of video footage from TOAD surveys conducted during MARAMP 2003 and in 2004 provide information about benthic habitats, typically at depths of 20–150 m (see Section 2.2.4: "Optical Validation"). Overviews of REA and towed-diver surveys and descriptions of sampling design and survey methods specific to each ecological discipline are presented in the remainder of this section.

Table 2.4a. Summary of biological and benthic habitat data presented in this report from REA, towed-diver, and TOAD surveys.

Discipline	REA Surveys	Towed-diver Surveys	TOAD Surveys
Habitat Characterization	–	• Cover (%) of sand • Habitat complexity	• Cover (%) of sand
Corals	• Composition and generic richness of coral communities • Cover (%) of live scleractinian (hard) corals • Coral density (# colonies m^{-2}) • Size-class distribution of corals • Distribution and prevalence of coral disease	• Cover (%) of live hard corals • Cover (%) of stressed corals	• Cover (%) of live hard corals
Algae	• Occurrence (%) by algal genera or functional group • Cover (%) of macroalgae (both calcified and fleshy), crustose coralline red algae, and turf algae • Distribution and density of coralline-algal disease	• Cover (%) of macroalgae (in 2003, combination of macroalgae and turf algae; in 2005 and 2007 macroalgae only) • Cover (%) of crustose coralline red algae	• Cover (%) of macroalgae
Other Macroinvertebrates	• Presence of macroinvertebrate species • Species richness of macroinvertebrates	• Distribution and abundance of crown-of-thorns seastars, giant clams, sea cucumbers, and sea urchins	–
Reef Fishes	• Composition and species richness of reef-fish communities • Biomass (kg 100 m^{-2}) of reef fishes	• Species composition of large fishes • Biomass (kg 100 m^{-2}) of large fishes (> 50 cm in total length)	–
Protected Species	–	• Sighting frequency of sea turtles (# individuals km^{-1})	–
Marine Debris	–	• Direct counts of derelict fishing gear, munitions, shipwrecks, and other man-made objects	–

2.4.1 Overview of REA Surveys

REA surveys are investigations that provide data at a high quantitative level and moderate taxonomic resolution for communities of corals, algae, other macroinvertebrates, and reef fishes. During MARAMP 2003, 2005, and 2007, the majority of REA surveys were conducted along the forereef slopes of islands at depths of 10–20 m. However, additional surveyed habitats included a lagoon-type patch reef in the caldera of Maug Islands and offshore oceanic banks at Pathfinder and Santa Rosa Reefs.

The biological assessment teams used specific methodologies targeting their respective biological communities. These methodologies overlapped and complemented each other to ensure that collected data were representative of the biological state at each REA site. A timeline of methods development for each ecological discipline is shown in Tables 2.4.1a and b, and the methods used by each assessment team are discussed in the corresponding ecological discipline sections.

During REA surveys, biological assessment teams followed highly structured protocols that were repeated at each REA site (Fig. 2.4.1a). Upon arrival at a REA site, 3 teams of divers—a fish team, a coral team, and a combined algal and macroinvertebrate team—entered the water over consecutive time intervals to avoid congestion along the transect lines. The fish team was the first team to enter the water and begin surveys, followed by the coral team and then the combined algal and macroinvertebrate team. The interdisciplinary survey effort at each site took 60–80 min to complete.

Table 2.4.1a. Timeline of methods development for each of the parameters measured using REA for corals, algae, and coral and coralline-algal disease. Line-point-intercept data was collected only for Guam in 2005. Methods used during MARAMP surveys included belt transect (BLT), quadrat (QS), line-point intercept (LPI), photoquadrat (PQS), roving diver (RD), and voucher specimen (VS).

Year	Corals and Coral Disease					Algae and Algal Disease			
	Generic richness and composition	Cover (%) of live corals	Colony density (# colonies m^{-2})	Size class	Disease prevalence	Occurrence (%) of algal genera	Cover (%) of algae	Species presence	Disease density
2003	QS	—	QS	QS	—	PQS	PQS	PQS, VS, RD	—
2005	QS, BLT	LPI	QS, BLT	QS, BLT	—	PQS	PQS, LPI	PQS, VS, RD	—
2007	QS, BLT	LPI	QS, BLT	QS, BLT	BLT	PQS	PQS, LPI	PQS, VS, RD	BLT

Table 2.4.1b. Timeline of methods development for each of the parameters measured using REA surveys for macroinvertebrates and reef fishes. Methods used during MARAMP surveys included belt transect (BLT), quadrat (QS), stationary-point count (SPC), and roving diver (RD).

Year	Macroinvertebrates		Reef Fishes		
	Species presence	Species richness	Total fish biomass (all sizes)	Fish biomass (> 25 cm in total length)	Species richness
2003	BLT, RD	—	BLT	—	BLT, SPC, RD
2005	BLT, RD	BLT, RD	BLT	SPC	BLT, SPC, RD
2007	BLT, QS	—	BLT	SPC	BLT, SPC, RD

Selection of REA Survey Sites and Transect Locations

REA sites were selected in 2003 for MARAMP 2003 and, when possible, revisited during MARAMP 2005 and 2007; a few additional sites were added in 2005 and 2007. Randomization methods were not used for site selection in 2003. CRED chose REA sites in consultation with the resource management agencies of each jurisdiction, including the CNMI DFW (Mike Trianni and Kate Moots) and DEQ (Fran Castro and Peter Houk) and the Guam DAWR (Trina Leberer). The following aims were considered during REA site selection: (1) a range of survey sites representative of the benthic and reef-fish habitats around each island or reef, (2) a mixture of sites within and outside of marine protected areas, (3) a mixture of sites likely to have been affected significantly by human activities and sites likely to have little human disturbance, (4) some sites adjacent to local villages, and (5) a number of sites that could be compared to and complement previous assessment and monitoring work done by local agencies. Additionally, it is important to note that wave exposure, weather conditions, and other environmental factors, such as currents, can limit access to REA sites and affect CRED's ability to survey sites again in subsequent MARAMP survey years.

REA METHODS

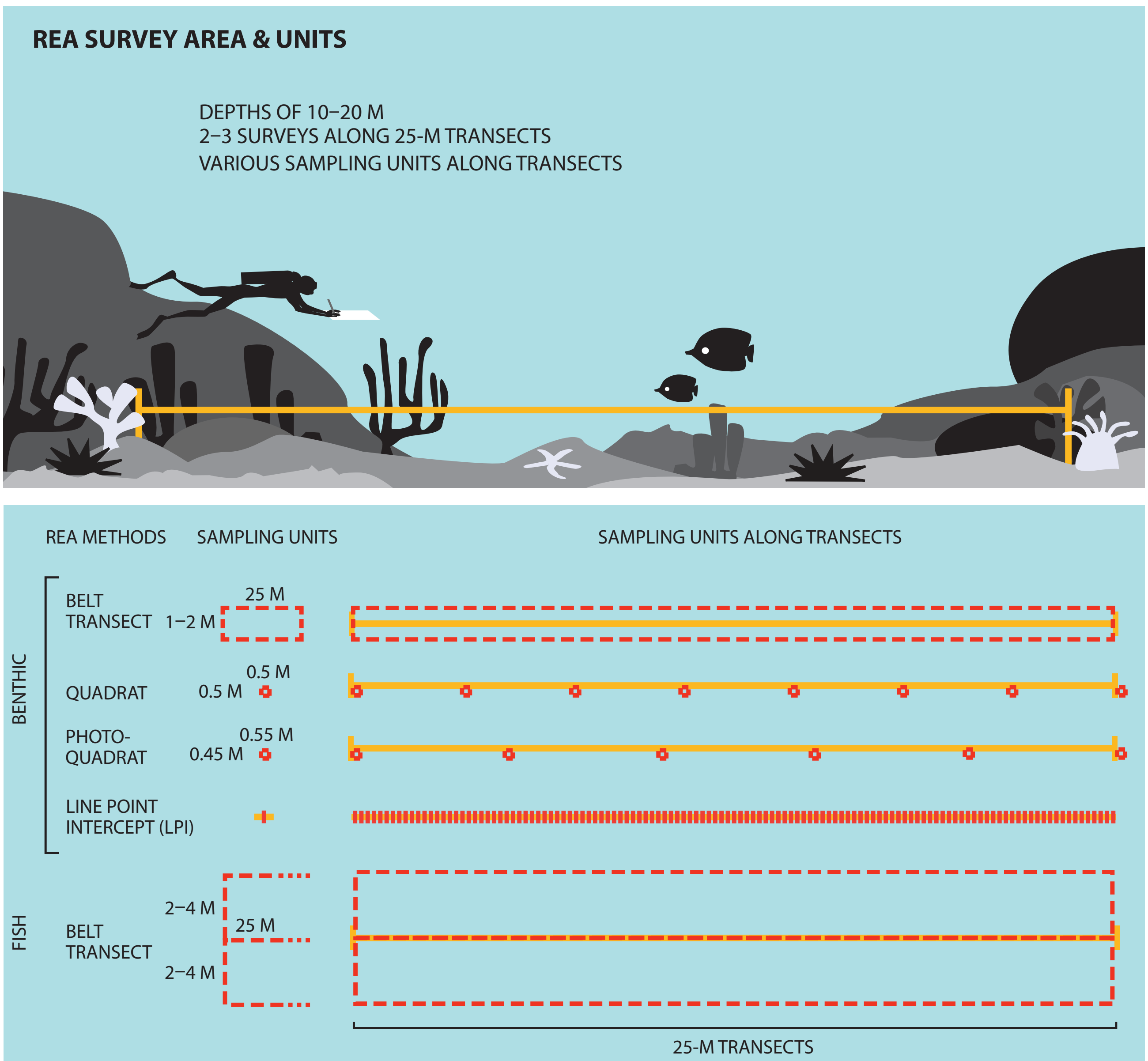


Figure 2.4.1a. Schematic diagram of survey areas and sampling designs for REA survey methods used during MARAMP 2003, 2005, and 2007.

The nonrandom nature of site selection places limits on the degree to which biotic metrics, such as percentage of cover, density, diversity, and disease prevalence of corals and coralline algae, can be extrapolated through statistical inference to the larger population around an island or bank. Because transects were not placed at the exact same location at a REA site each year and transects may not be representative of a site, interannual site comparisons need to be approached with caution. Variations in survey results between MARAMP survey years can result from transect placement and the addition of REA sites in subsequent years. However, revisiting the same REA sites each cruise does provide a basis for quantifying temporal trends in condition, which is a priority of CRED's long-term monitoring efforts.

At each REA site, 3 transect lines typically were deployed by the REA fish survey team, which was the first team to enter the water. All benthic disciplines used the first 2 transect lines and the fish survey team used all 3 transect lines as the geographical reference to guide their selection of point, area, or quadrat placement. Transects at each site were deployed (1) with a focus on hard-bottom communities, (2) along an isobath, to the extent possible, and (3) into the prevailing current. The latter was an important safety consideration that facilitated divers working against the current at the start of a dive but swimming with the current towards the end of a dive when they might be fatigued. Each discipline—corals, coral disease, algae, algal disease, other macroinvertebrates, and reef fishes—used survey protocols driven by (1) accepted methods within its discipline (Maragos et al. 2004; Houk et al. 2005; Preskitt et al. 2004; Brock 1982), (2) the number of divers available, and (3) NOAA safety guidelines (e.g., proximity to a buddy).

2.4.2 Overview of Towed-diver Surveys

Towed-diver surveys are used to characterize benthic habitats and to quantify the abundance and spatial distribution of ecologically and economically important fish, coral, algal, and macroinvertebrate taxa over an area that is much broader than the areas surveyed using REA methods. Importantly, towed-diver surveys also are able to access exposed coasts (e.g., windward-facing shores and high-swell conditions) that cannot always be surveyed using REA techniques.

During MARAMP 2003, 2005, and 2007, all towed-diver surveys were conducted along the forereef slopes of the islands of Guam and the CNMI at depths of 10–20 m. Additional surveys were completed on offshore banks only in 2003 and 2005. Towed-diver surveys were designed to cover as many habitat types (e.g., slope, lagoon, and bank) and as much of a complete revolution around each island as time allowed and to survey along a relatively constant isobath (typically 15–20 m). Around small islands, multiple circumnavigations were conducted targeting different isobath depths (e.g., 5, 15, and 25 m). Each towed-diver survey generally covered linear distances of 1.5–2.5 km.

In addition to the primary observations for each ecological discipline, towed divers were tasked with recording unusual or important sightings that included significant biological or habitat gradients, shipwrecks, unexploded ordinance or munitions, and derelict fishing gear or other types of marine debris located on the seafloor. Sightings of "species of concern," such as direct counts and size estimations of sea turtles, were also recorded during towed-diver surveys.

Towed-diver surveys were conducted by teams of 4 divers who alternated responsibilities between data gathering and boat handling. A pair of divers was towed ~ 60 m behind a small boat, a 6-m survey launch from SAFE Boats International (Port Orchard, Wash.), with 1 diver tasked with benthic data collection and 1 diver tasked with data collection on large fishes (> 50 cm in total length; Fig. 2.4.2a). Each diver made observations over a visually estimated 10-m swath (5 m out on each side of their respective tow lines, which act as transect lines). Towed at typical speeds of 0.5–1.3 m s^{-1} (1–2.5 kt), divers attempted to maintain their position ~ 1 m above the seafloor. Each survey took ~ 50 min, and 4–6 surveys were generally completed during each field day.

To georeference all data collected during towed-diver surveys, a GPS receiver located on the small boat was programmed to record longitude and latitude coordinates (waypoints) every 5 s. When towed divers were ready to begin recording data, they signaled to the coxswain, who then marked a waypoint indicating the start point of a towed-diver survey. The coxswain maintained speed and steered the small boat along a predetermined depth contour, using as guides a bathymetric chart, a singlebeam echosounder, and shoreline features (when present). "OK" signals were sent to the small boat every 5 min to inform the coxswain of the diver's status, and "mark" signals were sent to record any sites of natural or anthropogenic interest. Another coded signal was sent to the small boat to record the end-position of each survey.

The towed-diver platforms, or towboards, used by CRED were constructed of StarBoard (King Plastic Corp., North Port, Fla.) marine polymer sheets ~ 100 × 50 × 2 cm. Each towboard was outfitted with an SBE 39 temperature and pressure (depth) recorder set to record at 5-s intervals, 2 stopwatches for survey timing, an Uwatec bottom timer (Johnson Outdoors

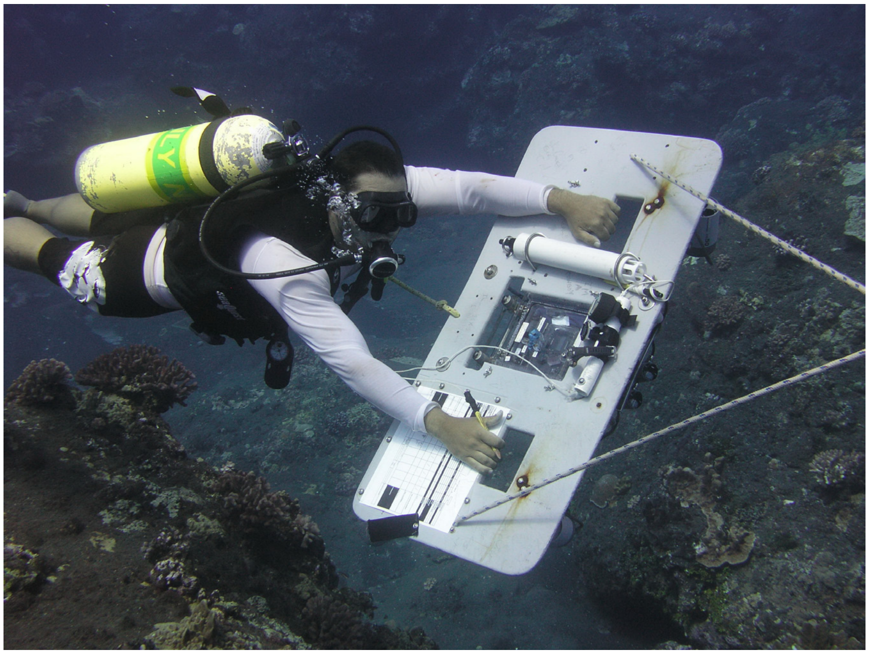
Inc., Racine, Wis.), and a vinyl data sheet. All timing devices were set to Greenwich Mean Time and synchronized each morning using the calibrated clock on the research vessel.

Benthic towboards (Kenyon et al. 2006) were outfitted with a downward-facing Canon EOS-10D digital still camera (Canon Inc., Tokyo) in a waterproof housing attached to the underside of each towboard in a "crash-proof," stainless steel bracket. Attached to the camera housing were 2 Ikelite strobes (Ikelite Underwater Systems, Indianapolis, Ind.) and 2 waterproof lasers calibrated for an intralaser distance of 15 cm. The camera automatically and repeatedly photographed the seafloor at 15-s intervals. These benthic images have been archived as a durable record of the towed-diver-benthic-survey tracks. CRED personnel and partners are analyzing these photographs for benthic composition to the functional group level.

Fish towboards were outfitted with a forward-facing Sony DCR-PC1000 MiniDV Handycam digital video camera (Sony Corp., Tokyo) in a Gates waterproof housing (Gates Underwater Products, Poway, Calif.) and crash-proof bracket similar to the one used on benthic towboards. These forward-facing cameras were used to collect streaming video images on Mini DV. Video footage from these cameras was archived as a durable record of the towed-diver-fish-survey tracks.

Data from towed-diver surveys were collected through direct diver observations and electronic instrumentation attached to towboards. Divers recorded observations every 5 min over a survey segment length of ~ 200 m, summarizing the benthic composition and ecologically or economically important fishes and macroinvertebrates encountered throughout each survey segment. A typical 50-min towed-diver survey included a total of 10 segments, although the actual time and length of surveys occasionally varied depending on environmental conditions and diving or logistical constraints. Diver observations and accessory instrument data collection techniques specific to each ecological discipline are discussed later in this chapter.

Figure 2.4.2a. Towed diver conducting a survey at Pagan. *NOAA photo Robert Schroeder*



During MARAMP 2005 and 2007, specific survey routes were preprogrammed into the small-boat GPS prior to initiating field activities, based on the towed-diver-survey tracks from MARAMP 2003. This preprogramming was done to enable as much track, target depth, and area overlap with previous years as possible.

Methods for towed-diver benthic surveys changed between MARAMP survey years to fine-tune data resolution and reduce task loading of divers (Table 2.4.2a). These changes generally were limited to 2 aspects of towed-diver-survey protocols: classification of benthic substrate categories and estimation of percentage of cover for benthic substrates. More information on variation in classification is provided in Tables 2.4.4a, 2.4.5a, and 2.4.6a.

When making temporal comparisons of results from towed-diver surveys, consider that minor fluctuations in estimates may have resulted from differences between MARAMP years in number of surveys conducted, survey depths, observer experience, and encounter rates and do are necessarily indicative of changes in the benthic or fish communities surveyed.

Table 2.4.2a. Summary of changes in the towed-diver survey method used during MARAMP 2003, 2005, and 2007.

Procedure	Description
Benthic cover estimates	Recorded to nearest percentage in 2003 and in 10 percentage bins in 2005 and 2007 (Table 2.4.3a)
Reef fish surveys	360° scan conducted during the first minute of each 5-min survey segment only in 2003
Marine debris sightings	Recorded as a direct part of method in 2003 but solely within observer comments in 2005 and 2007
Substrate Classification	**Description**
Rubble	Only rubble that was not visibly encrusted by macroalgae, calcareous algae, or corals was included in 2005 and 2007, but rubble could be encrusted in 2003 (Table 2.4.4a)
Carbonate pavement	Only recorded in 2003 (Table 2.4.4a)
Soft corals	Only recorded in 2005 and 2007 (Table 2.4.5a)
Stressed corals	Monitoring of corals that appeared stressed was improved in 2005 (Table 2.4.5a)
Recently dead corals	Only recorded in 2003 (Table 2.4.5a)
Macroalgae (both fleshy and calcified)	Turf algae was included only in 2003 (Table 2.4.6a)

2.4.3 Data Processing: REA and Towed-diver Surveys

At the end of each day of REA benthic survey operations, GPS waypoints were downloaded and quantitative data were entered into Microsoft Excel spreadsheets. These data were later transferred into a Microsoft Access database and quality controlled. Data from towed-diver datasheets were transcribed into a Microsoft Access database and quality controlled at the end of each day. The Microsoft Access database is delineated according to pre-established regions: Mariana Archipelago, main Hawaiian Islands, Northwestern Hawaiian Islands, American Samoa, and the Pacific Remote Islands Marine National Monument.

Following each day of field operations for towed-diver surveys, the GPS waypoints collected from a GPS receiver mounted on the small boat and the depth and temperature data from the SBE 39 on each of the towboard platforms were downloaded. A custom built Python script (Python Software Foundation, Wolfeboro Falls, NH) in an ArcGIS environment was used for processing these waypoints and the corresponding depth and temperature data. This data processing generated 4 standard shapefiles: GPS points, dive points, segments, and surveys. GPS points represent the raw, uncorrected, GPS waypoints, and they were used to generate the other standard shapefiles. The Python script clipped GPS points to the start and stop waypoints of a survey and imported the corresponding depth and temperature data using time stamps. Then, the script generated dive points from the clipped GPS points and repositioned them to the location of the divers based on the track, speed, and course of the boat and depth of the divers.

Two additional attributes were added to the dive points, creating a unique serial number for each 5-min segment and 50-min survey by using the date, survey, and segment numbers (e.g., the serial number, or "Dive ID," for survey 1 on May 16, 2007, is 200705161, and the serial number, or "Segment ID," for segment 5 of survey 1 is identified as 20070516105). The survey and segment shapefiles, then, were generated by lacing together each of the dive points and grouping them by either Dive ID or Segment ID. These serial numbers also were the basis for the join (or union) between the fish or benthic data and the geodatabase, allowing these data to be mapped to specific geographic locations.

Results from towed-diver benthic surveys were used to create several different types of maps: (1) habitat characterization of habitat complexity, sand cover, and cover of live scleractinian (hard) corals (see Section 2.2.4: "Optical Validation"); (2) cover of live hard corals, stressed corals, macroalgae, and crustose coralline red algae; (3) macroinvertebrate densities and distribution, and (4) biomass and distribution of large fishes (> 50 cm in total length).

Table 2.4.3a. Bin categories for estimates of benthic cover (%) used in towed-diver surveys during MARAMP 2005 and 2007.

Bin	Benthic Cover (%)	Midpoint
1	0.1–1	0.5
2	1.1–5	2.5
3	5.1–10	7.5
4	10.1–20	15
5	20.1–30	25
6	30.1–40	35
7	40.1–50	45
8	50.1–62.5	56.25
9	62.6–75	68.75
10	75.1–100	87.5

Diver observations for each 5-min survey segment were graphically projected onto ArcGIS 9.3 maps using the midpoint for each survey segment (segment length, ~ 200 m; midpoint, ~ 100 m). For estimates of benthic cover, values from MARAMP 2003 were projected as the midpoint of the percentages recorded by towed divers, while values from MARAMP 2005 and 2007 were projected as the midpoint of the binned observations (Table 2.4.3a). Macroinvertebrate values were projected as the total number of organisms observed per survey segment or as the midpoint of their binned range. Densities were calculated as the total number of macroinvertebrates observed during a survey divided by the area covered during that survey (10-m survey width multiplied by survey length and presented per 100 m^2). For habitat characterization maps only, results for all 3 MARAMP survey years are combined and interpolated (see Section 2.4.4: "Benthic Habitat Complexity and Substrates").

Within this report, summary statistics from REA and towed-diver-survey data are presented primarily as standard error of the mean (SE), since SE quantifies the precision of an estimate of a population mean, factoring in both sample size and standard deviation of the mean (SD). Because SD quantifies the variability within a set of surveys, summary statistics of depths of towed-diver surveys are presented as SD. These summary statistics are reported in the same unit of measure as their associated mean values.

2.4.4 Benthic Habitat Complexity and Substrates

Information about habitat complexity and substrate type from towed-diver surveys provides context for the analyses of biological data collected during the same towed-diver surveys. REA surveys collected data about substrate cover that give context to results from surveys at REA sites. Analyses of video footage from TOAD surveys also assists in benthic habitat characterization.

TOAD surveys were conducted during MARAMP 2003 and in 2004, and observations from analyses of video footage collected from these surveys were classified into benthic habitat categories that included substrate types, such as sand, rock, and rubble, as well as categories for living cover (for a full list of classification categories, see Section 2.2.4: "Optical Validation"). REA surveys using the line-point-intercept method in 2007 (and 2005 at Guam) collected data on a few substrate categories in addition to information on living cover. These REA surveys assigned benthic elements to 1 of 9 categories: carbonate pavement, rock, live corals (scleractinian, hydrocorals, and *Heliopora coerulea*), dead corals, crustose coralline red algae, macroalgae (both calcified and fleshy), coral rubble, sand, and other sessile invertebrates.

Data from towed-diver surveys were used to create habitat characterization maps of sand cover and habitat complexity and for optical validation of acoustic or satellite-derived information (see Section 2.2.4: "Optical Validation"), in addition to their use in producing the information about living cover presented for each ecological discipline in this report.

At 5-min intervals, benthic towed divers recorded a suite of information that included the predominant reef zone, estimates of average topographic complexity of habitats, and estimates of average percentages of cover for benthic substrate types. Reef zone categories included forereef, backreef, lagoon, bank, bank escarpment, and channel. Benthic substrate cover categories included sand, rubble, and carbonate pavement, as well as live and stressed hard corals, macroalgae (both fleshy and calcified), and crustose coralline red algae (Tables 2.4.4a, 2.4.5a, and 2.4.6a).

Estimates of habitat complexity during towed-diver surveys were subjective assessments of the benthic topographical diversity and complexity classified on a 6-level categorical scale: low, medium-low, medium, medium-high, high, and very high (Fig. 2.4.4a). For example, low habitat complexity is often associated with flat sand plains or rubble habitats; medium habitat complexity is often associated with small-to-moderate spur-and-groove, coral, or boulder habitats; and high and very high habitat complexity are often observed as high or extreme vertical relief associated with steep, spur-and-groove canyons, pinnacles, and walls.

Because of changes in methodologies regarding substrate type (Table 2.4.4a), no maps of rubble cover are presented in this report. In addition, substrate and pavement data were collected during MARAMP 2003 but not during MARAMP 2005 or 2007. Because these diver observations were limited to one year, they are not presented in this report. However, percentage of cover for hard substrate and pavement can be inferred from the sand cover maps in this report. All other benthic substrate categories used to create habitat characterization products remained the same for towed-diver surveys conducted in 2003, 2005, and 2007.

Estimates of benthic features from towed-diver surveys were plotted in ArcGIS 9.3 using the midpoint of each 5-min survey segment (Table 2.4.3a). For benthic habitat characterization maps, results from MARAMP 2003, 2005, and 2007 surveys were combined, and then an inverse distance weighting (IDW) interpolation function (ArcGIS 9.2) was applied to this combined data set. The IDW function produced a continuous plot of the salient benthic features around each island. Where towed-diver surveys from different years overlapped, this interpolation reflects the mean spatial distribution of a benthic substrate category over the time series, averaging out temporal changes in benthic cover. Where surveys from different years did not overlap, these interpolated values provide predicted spatial distribution of benthic habitats.

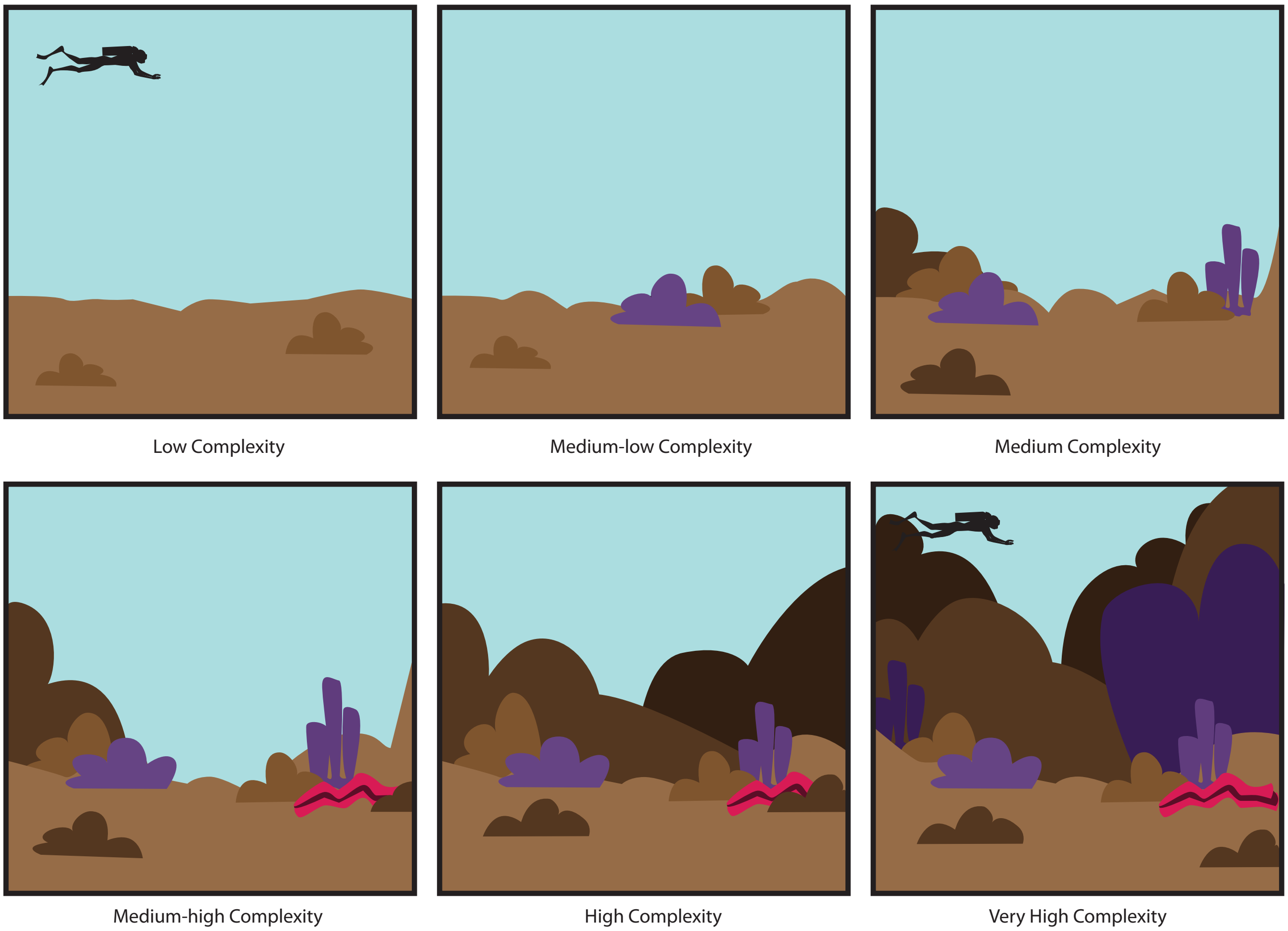


Figure 2.4.4a. Examples of the 6 categories used to classify habitat complexity: low, medium-low, medium, medium-high, high, and very high. As they regularly encounter multiple habitat types, towed divers estimate average complexity during each 5-min observation segment over a survey swath of ~ 200 x 10 m (~ 2000 m²).

Table 2.4.4a. Descriptions of the benthic composition categories of sand, rubble, and carbonate pavement used in towed-diver surveys during MARAMP 2003, 2005, and 2007 (Kenyon et al. 2006). Data for rubble and carbonate pavement are not provided in this report. For descriptions of coral and algal categories, see Tables 2.4.5a and 2.4.6a in this chapter.

Category	Year	Description
Sand	2003 2005 2007	Unconsolidated sediment, ranging in texture and size from fine to coarse and including both inorganic (eroded rock) and organic (eroded fragments of calcareous organisms) sediments.
Rubble	2003	Unconsolidated fragments of coral skeleton or reef rock of sizes larger than sand. May be visibly encrusted by macroalgae, calcareous algae, or corals.
Rubble	2005 2007	Unconsolidated fragments of coral skeleton or reef rock of sizes larger than sand. Only rubble that was not visibly encrusted by macroalgae, calcareous algae, or corals was included.
Carbonate Pavement	2003	Consolidated substrate, typically composed of calcareous or basaltic elements, which have become cemented together by biogenic and physical processes.

2.4.5 Corals and Coral Disease

Coral communities were examined using primarily REA and towed-diver surveys during MARAMP 2003, 2005, and 2007. Towed-diver surveys were used to assess cover of live and stressed corals. Three different REA methodologies—belt transect, quadrat, and line-point intercept—were used to survey several parameters: coral cover, coral-colony density, generic richness and relative abundance, coral size-class distribution, and distribution and prevalence of coral disease.

REA surveys measured anthozoan and hydrozoan corals. Anthozoan corals are any of the Cnidarian class Anthozoa, such as the corals and sea anemones, that have radial segments and grow singly or in colonies. Hydrozoan corals are any of the Cnidarian class Hydrozoa, such as the colonial hydrocorals that secrete a calcium carbonate skeleton.

Towed-diver surveys focused on 2 types of anthozoans: corals of the order Scleractinia, also called hard or stony corals, and soft corals, which are of the order Alcyonacea. In this report, coral-cover data from towed-diver surveys is reported only for hard corals.

TOAD surveys were conducted during MARAMP 2003 and in 2004, and observations from analysis of TOAD video collected during these surveys were classified into benthic habitat categories that included hard corals (see Section 2.2.4: “Optical Validation”).

During towed-diver benthic surveys, divers recorded a suite of information at 5-min intervals that included estimates of average percentages of cover for live and stressed hard corals as well as for other benthic substrate types. These estimates were recorded to the nearest percentage during MARAMP 2003 and within 10 percentage bins during MARAMP 2005 and 2007. Descriptions of benthic substrate categories for hard corals and the percentage bins used in 2005 and 2007 are provided in Tables 2.4.5a and 2.4.3a.

Because towed-diver surveys use visual estimates for coral cover, results can be subject to observer variability both within and among MARAMP survey years. While every effort is made to calibrate among observers, as well as to replicate survey-track lines among years, minor deviations in lateral position of the small boat that tows divers can result in considerable survey depth and strata disparities among survey years.

Table 2.4.5a. Descriptions of benthic composition categories related to coral cover used in towed-diver surveys during MARAMP 2003, 2005, and 2007 (Kenyon et al. 2006). Data for recently dead corals are not provided in this report. For descriptions of substrate and algal categories see Tables 2.4.4a and 2.4.6a in this chapter.

Benthic Category	Year	Description
Live Hard Corals	2003 2005 2007	All live hard corals observed in a survey swath. These observations included both stressed (see description below) and unstressed corals. Soft corals or dead corals were not included. Live corals were characterized by colonies or portions of colonies covered with living tissue. Living tissue usually appeared colored (e.g., olive green, brown, or bluish lavender) because of the presence of pigments in coral tissue or of symbiotic zooxanthellae. Stressed coral tissue could have appeared pale or completely white.
Stressed Corals	2005 2007	Live hard corals that appeared stressed or bleached as a result of loss of coloration. Signs of stress included pale-to-white coloration caused by bleaching, predation by crown-of-thorns seastars, disease, or recent coral death. Corals could be discolored, malformed, or stricken with tumors. Estimates of stressed-coral cover from MARAMP 2003 are not included in this report.
Recently Dead Corals	2003	Bare white colonies (or portions of them) that had lost living tissue and were not visibly encrusted by macroalgae or epiphytes were classified as dead coral. Lack of encrustation suggested tissue death was recent relative to encrusted portions of dead colonies. Dead coral with macroalgae growth, epiphytes, or other forms of substrate cover were classified as macroalgae (both fleshy and calcified) or other substrate category. Since, in some cases, it could have been hard to differentiate between recently dead and severely bleached corals, both were classified as stressed corals.
Soft Corals	2005 2007	All soft corals observed in a survey swath.

At each REA site, surveys were conducted by 3 dive teams, 1 of which consisted of 2 divers who performed coral and coral-disease surveys. The coral team entered the water and began to work along the first of 2 transect lines ~ 20 min after the fish team entered the water (Fig. 2.4.1a).

The REA methods employed by the coral team varied depending on the biologists conducting the surveys. For most parameters, personnel from CRED used the belt-transect method, and personnel from the CNMI DEQ used the quadrat method. Each method has intrinsic biases, in part because of the difference in areas surveyed (~ 4 m versus 50–100 m per site). The consequences of these biases are discussed in the "Coral Surveys" section of each island chapter. Only at REA sites surveyed by CRED personnel was the line-point-intercept method used to estimate percentages of live coral cover. The spatial and temporal variation of REA coral methodologies is summarized in Table 2.4.5b. Temporal comparisons of survey results are not appropriate for islands (Saipan, Aguijan, Rota, and Guam) where the belt-transect method was used during MARAMP 2007 but the quadrat method was used during previous survey years. Thus, in Chapter 3: "Archipelagic Comparisons," figures present colony-density and size-class data only from REA surveys conducted in 2007.

Results from REA surveys of coral communities were used to calculate generic richness and relative abundance, coral-colony density, size-class distributions, and percentages of cover for live hard corals for each REA site. Generic richness was computed as the maximum number of coral genera recorded within belt transects or quadrats at a site. Coral density was calculated by dividing the total number of colonies within all belt transects or quadrats at a site by the total area surveyed. Coral size-class histograms were created by calculating the relative frequencies of all hard corals in each of the 7 size classes recorded during belt-transect or quadrat surveys. Live coral cover was calculated as the average of results from line-point-intercept surveys on both transects at a site.

Coral cover from REA surveys is presented only from MARAMP 2007, the first year in which the line-point-intercept method was used in the Mariana Archipelago, with the exception of Guam, where this REA method was first used in 2005. Another REA method, the photoquadrat method, was used by the algal assessment team to survey the composition of benthic habitats at REA sites during the 3 MARAMP survey years. Analyses of benthic photographs from these surveys are underway.

Table 2.4.5b. Methods used during MARAMP 2003, 2005, and 2007 for REA coral surveys by island, year, and metric: belt transect (BLT), quadrat, and line-point intercept (LPI). Other metrics include colony density, generic richness and relative abundance, and size class. Coral cover was not assessed using these REA methods in 2003 and only assessed at Guam in 2005. One site at Tinian, TIN-04, was surveyed using the quadrat method in 2007.

Island	2003		2005		2007	
	Cover (%)	Other metrics	Cover (%)	Other metrics	Cover (%)	Other metrics
Guam	–	Quadrat	LPI	BLT	LPI	BLT
Rota	–	Quadrat	–	Quadrat	LPI	BLT
Aguijan	–	Quadrat	–	Quadrat	LPI	BLT
Tinian	–	Quadrat	–	Quadrat	LPI	BLT, Quadrat
Saipan	–	Quadrat	–	Quadrat	LPI	BLT
Anatahan	–	Quadrat	–	Quadrat	LPI	Quadrat
Sarigan	–	Quadrat	–	Quadrat	LPI	Quadrat
Guguan	–	Quadrat	–	Quadrat	LPI	Quadrat
Alamagan	–	Quadrat	–	Quadrat	LPI	Quadrat
Pagan	–	Quadrat	–	Quadrat	LPI	Quadrat
Agrihan	–	Quadrat	–	Quadrat	LPI	Quadrat
Asuncion	–	Quadrat	–	Quadrat	LPI	Quadrat
Maug	–	Quadrat	–	Quadrat	LPI	Quadrat
Farallon de Pajaros	–	Quadrat	–	Quadrat	LPI	Quadrat
Reefs and Banks	–	Quadrat	–	Quadrat	LPI	Quadrat

Belt-transect Surveys

The belt-transect method was used to quantitatively assess generic richness, colony density, and size class of coral colonies. At the beginning of each dive, the belt width was subjectively dictated by perceived colony density: a width of 1 m was used in high-density areas, while a width of 2 m was used in low-density areas. At each REA site, the coral diver surveyed two 25-m transect lines, recording the maximum diameter of all coral colonies whose centers fell within each belt transect (total survey area = 50–100 m^2). Colonies were recorded to genus level and assigned, by visual estimation, to 1 of 7 size classes: ≤ 5 cm, 6–10 cm, 11–20 cm, 21–40 cm, 41–80 cm, 80–160 cm, and > 160 cm (this binning of coral-colony size classes was based on Mundy [1996]). Estimation of individual coral colony boundaries in the field could be complicated especially for species with life history strategies involving clonal propagation (e.g., *Acropora muricata*) or fissioning (e.g., *Porites lobata*). When estimating coral-colony boundaries, consideration was given to tissue color, interfaces (e.g., skeletal ridges) with neighboring colonies of the same species, and variations in growth forms. If determinations of individual colony boundaries could not be made on these criteria alone, conspecific areas of live tissue separated by more than 10 cm were considered to be separate colonies. All scleractinian, hydrozoan, and octocorals were included in this census.

Quadrat Surveys

The quadrat method was used to quantitatively assess generic richness, colony density, and size class of coral colonies. Along the length of a single 50-m transect line at each site, a quadrat (0.5 × 0.5 m) was haphazardly placed on hard-bottom substrate with corals for a combined total of either 15 (in 2003) or 16 (in 2005 and 2007) times per site (total survey area = 3.75 or 4 m^2 per site). Each scleractinian or hydrozoan colony whose center lay inside a quadrat was identified to species (or genus, for small colonies in which species characteristics had not yet developed), and their maximum and perpendicular diameters were measured (Houk et al. 2005). Octocorals were not included in this census, with the exception of the blue coral *Heliopora coerulea*.

Line-point-intercept Surveys

The line-point-intercept method (Hill and Wilkinson 2004) was used to assess percentage of cover for live corals and other benthic elements at REA sites surveyed at Guam during MARAMP 2005 and at all REA sites surveyed during MARAMP 2007. A coral diver swam along two 25-m transect lines recording at 50-cm intervals all benthic elements falling directly underneath the transect lines. Benthic elements were assigned to 1 of 9 benthic categories: live corals (scleractinian, hydrocorals, and *Heliopora coerulea*), dead corals, carbonate pavement, rock, crustose coralline red algae, macroalgae (both calcified and fleshy), coral rubble, sand, and other sessile invertebrates. Benthic elements were identified to the lowest taxonomic level possible. Cover of turf algae was derived from estimates of cover of dead corals, pavement, and rock.

Surveys for Coral Disease, Syndromes, and Predation

Coral diseases and syndromes, as well as predation scars from crown-of-thorns seastars (*Acanthaster planci*) or corallivorous snails, such as snails from the genus *Drupella*, were quantified using the belt-transect method at each REA site. Coral diseases were first surveyed during MARAMP 2007. In a complementary effort, during MARAMP 2005 and 2007, towed-diver surveys estimated percentages of stressed-coral cover: live hard corals that appeared stressed or bleached as a result of loss of coloration (Table 2.4.5a).

At each REA site, the occurrence of coral disease was quantitatively assessed along two 25-m transect lines, following a methodology tested and implemented at Johnston Atoll and the Northwestern Hawaiian Islands (Brainard et al. 2005; Aeby 2006). At the beginning of each dive, subjectively perceived abundance of coral disease dictated the width of the belt: 2 m at disease-rich sites or where surge, currents, or rough seas precluded expanded surveys or 6 m at all other sites to tally a suffient number of cases of low-occurring incidences. Within belt transects, all diseased coral colonies were enumerated, measured, identified to the genus level, and assigned to 1 of 6 disease state categories (Vargas-Ángel and Wheeler 2009): skeletal growth anomalies, white syndrome (acute tissue loss), subacute tissue loss, pigmentation response, fungal infections, and other impaired health conditions, including algal and cyanophyte infections, tube-worm infestations, and syndromes of unknown etiology. In assessing coral health conditions, colonies exhibiting full, partial, or spotty bleaching were also tallied, and, thus, hereafter, bleaching is treated as a disease state—an impairment of normal function (Woebser 2006). Additionally, lesions attributable to predation by crown-of-thorns seastars (COTS) or corallivorous snails were also identified, measured, and enumerated. These counts were complemented with digital photography and tissue collections for future histological examination and verification. A measure of disease severity (percentage of colony affected) was assessed on a semi-quantitative scale from 0 to 5: 1 (mild), ≤ 10%; 2 (moderate), 11%–25%; 3 (marked), 26%–50%; 4 (severe), 51%–75%; 5 (acute), > 75%. In addition, distribution of colony lesions was described following Work and Aeby (2006).

To avoid spreading diseases, when sampling corals within a disease site, fist collections of apparently unaffected (healthy) individuals were conducted first, followed by collections of portions of diseased colonies that appeared unaffected (healthy on disease), and the diseased portions (lesions) of a colony were sampled last. Also, upon return to the ship, collection tools and dive gear were rinsed in bleach solution, thoroughly rinsed with freshwater, and air dried.

Descriptions of coral disease states used during REA surveys are provided in the paragraphs that follow. For more information on coral diseases, go to the CRED website at http://www.pifsc.noaa.gov/cred/coraldiseases.php. For each REA site, overall prevalence of coral disease was computed as the percentage of diseased colonies (counts) relative to the estimated total number of colonies at that site: P_O = (total number of disease cases × 100) ÷ (colony density × total area surveyed for presence of disease).

Skeletal Growth Anomalies

Lesions characterized by changes in normal shape or form of coral colonies, unusual growths, or protuberances associated with an abnormal deposition of the skeleton. Skeletal growth anomalies are caused by changes in the coral cells that deposit the carbonate skeleton, including the following changes: (1) hyperplasia, a process resulting in an increase in the number of cells in a tissue or organ, thereby increasing the bulk of that tissue or organ, and (2) neoplasia, a pathology resulting in the formation and growth of an undifferentiated mass of cells that continues after cellular stimulus ceases (Fig. 2.4.5a[a]).

White Syndrome (Acute Tissue Loss)

White syndrome is a collective term that describes lesions characterized by acute and rapid loss of tissue, leaving behind a sharp, clean band, where tissue is completely removed from a skeleton. A progression of filamentous and turf algae generally covers an exposed skeleton. These features contrast with the wide zone of white skeleton commonly exposed following COTS predation or the scalloped or irregular tissue front produced by the corallivorous gastropod *Drupella* of the subfamily Thaidinae (Fig. 2.4.5a[b]).

Subacute Tissue Loss

Subacute tissue loss is a collective term that describes lesions resulting in slow but progressive loss of tissue. Subacute tissue loss is distinguished from white syndrome by the narrow width of the zone of recently exposed skeleton. Because a particular type of gross lesion can present multiple microscopic manifestations, coral-disease assessments and studies require biopsies for histological, microbiological, and molecular evaluation and verification (Fig. 2.4.5a[c]).

Pigmentation Response

Lesions are characterized by patches of discolored, pink, purple, and blue-to-brown swollen tissue that often occur in irregular shapes and patterns, scattered on the surface of a colony or adjacent to the sediment or algal margins of a colony. Often, but not exclusively, lesions appear to be associated with small areas of tissue loss and allopathic and parasitic interactions with filamentous algae, cyanobacteria, polychaetes, molluscs, and trematodes. However, uncomplicated lesions are also fairly common (Fig. 2.4.5a[d]).

Fungal Infections

Lesions are characterized by patchy, dark discolorations that occur in irregular patterns, bands, or scattered on a coral surface. A progression of filamentous and turf algae may generally appear on cases where infections result in tissue loss. Microscopic examination reveals extensive endolithic fungal proliferation. Upward migration of fungal hyphae into the thecal cavity is generally associated with disruption of the polyp body wall and sloughing of gastrodermis (Fig. 2.4.5a[e]).

Compromised Health States and Other Syndromes of Unknown Etiology

Coral-algae, coral-cyanobacteria, and other biotic interactions such as barnacle and tube-worm infestations may result in an impairment or inhibition of normal coral functioning (e.g., growth, calcification, or reproduction). These morphologies, together with other unidentified cases, are grouped under "other lesions" in surveys for disease prevalence and presented in maps in this report under the category of "Other Diseases" (Fig. 2.4.5a[f]).

Bleaching

This condition is characterized by a reduction in intensity, or complete absence, of coloration within living coral, due to loss of pigmentation or expulsion of endosymbiotic zooxanthellae. Patterns of bleaching can vary, with only the upper surface or lower surface of a colony affected, and can also appear patchy, mottled, or as a circular blotch, ring, or wedge. Although bleaching is considered a generalized response to stressful conditions, it is a sign of disease when it results in an impairment or inhibition of normal coral functioning (e.g., growth, calcification, or reproduction) and colony death. Recent studies also indicate that bleaching can be caused by an intracellular bacterial pathogen of the genus *Vibrio* (Fig. 2.4.5a[g]).

Predation

Coral predators often leave scars devoid of tissue that may lead to decreased health status and increased susceptibility to algal overgrowth, invasion by other pathogens, or lower reproductive output. The pattern of tissue loss from predation often differs from tissue loss patterns from other causes. Scars characterized by wide zones of exposed coral skeleton are commonly observed following predation by COTS (Fig. 2.4.5a[h], right panel) or characterized by scalloped or irregular tissue fronts that are often produced by the corallivirous gastropod *Drupella* of the subfamily Thaidinae (Fig. 2.4.5a[h], left panel). In this report, predation is included in the values of overall prevalence shown for each REA site on coral disease maps, but predation cases are reported separately from disease prevalence in the text.

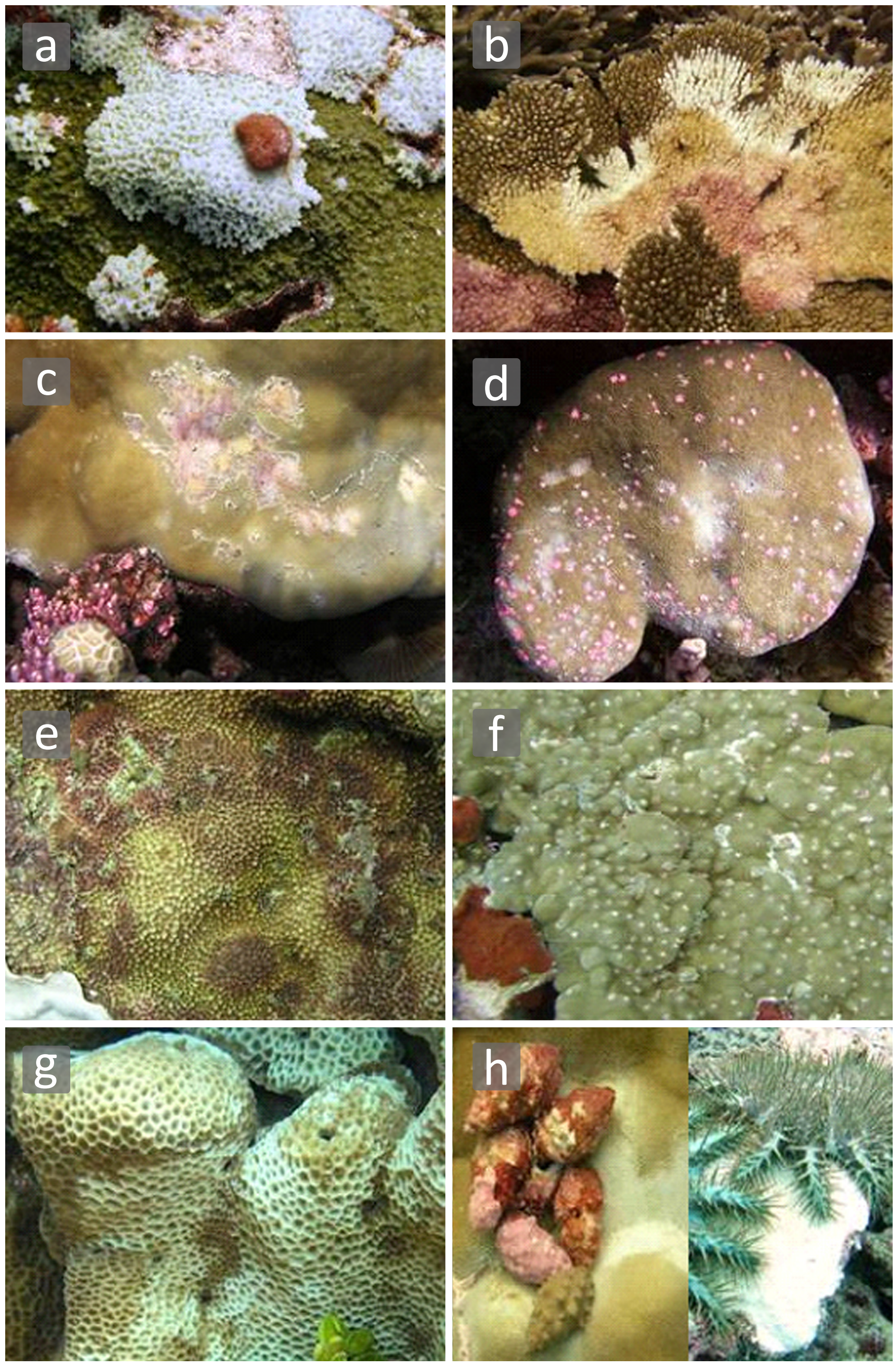


Figure 2.4.5a. Underwater photographs illustrating the field appearance of lesions affecting hard corals around Guam and the CNMI during MARAMP 2007: (*a*) skeletal growth anomalies on *Montipora* sp., (*b*) white syndrome (acute tissue loss) on *Acropora* sp., (*c*) subacute tissue loss on *Porites* sp, (*d*) pigmentation response on *Porites* sp., (*e*) fungal infection on *Pavona varians*, (*f*) "other lesions," specifically tube-worm infestation on *Porites* sp., (*g*) bleaching on *Gardineroseris planulata*, and (*h*) scars from predation by (*left*) *Drupella* snails and (*right*) COTS. *NOAA photos by Bernardo Vargas-Ángel*

2.4.6 Algae and Algal Disease

Algal communities were examined using primarily REA and towed-diver surveys during MARAMP 2003, 2005, and 2007. Cover of macroalgae (both fleshy and calcified), crustose coralline red algae, and turf algae was assessed using towed-diver surveys. Five methodologies—quadrat, photoquadrat, line-point intercept, belt transect, and voucher specimen—were used at REA sites to survey algal cover, occurrence of algal genera and functional groups, presence of algal species, and distribution and density of algal disease.

TOAD surveys were conducted during MARAMP 2003 and in 2004, and observations from analysis of TOAD video collected during these surveys were classified into benthic habitat categories that included macroalgae and crustose coralline red algae (see Section 2.2.4: "Optical Validation").

During towed-diver benthic surveys, divers recorded a suite of information at 5-min intervals that included estimates of average percentages of algal cover as well as of other benthic substrate types. These estimates were recorded to the nearest percentage during MARAMP 2003 and within 10 percentage bins during MARAMP 2005 and 2007. Descriptions of benthic substrate categories for algae and the percentage bins used in 2005 and 2007 are provided in Tables 2.4.6a and 2.4.3a.

Table 2.4.6a. Descriptions of benthic composition categories related to algal cover used in towed-diver surveys during MARAMP 2003, 2005, and 2007 (Kenyon et al. 2006). The macroalgae category included turf algae only in 2003. For descriptions of substrate and coral categories see Tables 2.4.4a and 2.4.5a in this chapter.

Benthic Category	Year	Description
Macroalgae	2003	Fleshy or frondose algae (e.g., species of *Sargassum*), heavily calcified algae (e.g., species of *Halimeda*), and turf algae.
Macroalgae	2005 2007	Fleshy or frondose algae (e.g., species of *Sargassum*) and heavily calcified algae (e.g., species of *Halimeda*). Turf algae were not included.
Crustose Coralline Red Algae	2003 2005 2007	Encrusting calcareous algal species observed within the survey swath. These encrusting algae deposit calcium carbonate as part of their structure, often giving a pinkish or lavender appearance to the encrusted substrate. In some areas these algae can also form three-dimensional spires.

At each REA site, surveys were conducted by 3 dive teams, 1 of which consisted of 2 algal biologists and 1 macroinvertebrate biologist who performed algal and macroinvertebrate surveys. About 10 min after the coral team entered the water, the combined algal and macroinvertebrate team entered the water and began to work along the first of 2 transect lines (Fig. 2.4.1a).

Algal populations at REA sites were surveyed to assess the diversity and relative abundance of algae in the Mariana Archipelago using the photoquadrat method and collection of voucher specimens. Percentages of algal cover were determined using the line-point-intercept method. The belt-transect method was used to estimate density of algal disease. The temporal variation of REA algal methodologies is summarized in Table 2.4.1a.

Observations from REA surveys of algal communities were used to calculate percentages of occurrence of algal genera and functional groups for each REA site. Percentage values of occurrence were calculated by summing the number of photoquadrats in which each algal genus or functional group was observed and dividing by 12, the total number of quadrats surveyed at a site. Percentages of occurrence were then used to create maps of algal distribution for each island or bank. In addition, algal composition results by island were calculated by summing the occurrence percentages for each algal genus or functional group and then dividing respective occurrence values by this sum.

Photoquadrat Surveys

The photoquadrat method, involving quadrats and photographic documentation, was used to examine algal communities. Quadrats were employed to assess the relative abundance of macroalgal genera and algal functional groups in the field. These estimates of abundance are considered relative because assessments for an alga observed in a quadrat, or photoquadrat, were relative to whichever other taxa were present in a photoquadrat. At each REA site, 12 photoquadrats of 0.18 m^2 (~ 16 × 23 cm) were surveyed along two 25-m transect lines. Six photoquadrats were located at randomly selected points along these transects (3 per transect), and 6 additional quadrats were placed at points 3-m perpendicular from each random point in the direction of shallower water (Preskitt et al. 2004; Vroom et al. 2005). Macroalgae were identified to genus level in the field, whereas crustose coralline red algae, branched coralline red algae, turf algae, and cyanophytes were lumped into functional group categories. In addition, each genus or functional group found in each quadrant was assigned a rank based on its relative abundance in that quadrant (with a rank of 1 being the most abundant). All ranked data for a given MARAMP survey year were collected by the same individual, minimizing the effects of observer bias.

Photographs were taken of each 0.18-m^2 quadrat assessed during these surveys to provide a quantitative data set for later, in-depth, species-level analyses of percentages of algal cover. At each REA site, 12 photographs were taken using digital still cameras (Fig. 2.4.6a). These benthic images, along with voucher specimen collections, form a permanent record of algal communities at each REA site. Results from analyses of these benthic images to the functional group level are available from CRED.

Roving-diver Surveys

A random swim, completed after each photoquadrat survey, augmented the number of macroalgal genera enumerated in photoquadrats at each REA site. For a 5-m swath on either side of the transect line, algal divers haphazardly recorded algal taxa not encountered in photoquadrats. These data are included in the counts of macroalgal genera and functional groups provided in Chapter 3: "Archipelagic Comparisons" and in Appendix B and Appendix C but not in the presence data presented for each MARAMP survey year in the island chapters.

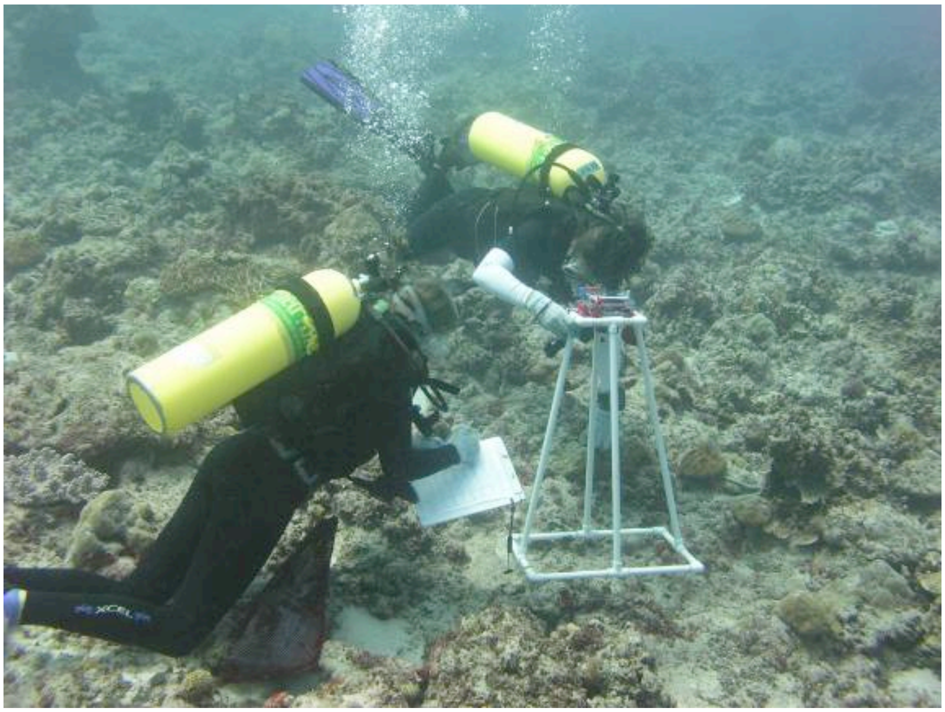
Line-point-intercept Surveys

The line-point-intercept method (Hill and Wilkinson 2004) was used to assess average percentage of cover of macroalgae, crustose coralline red algae, and other benthic elements at REA sites surveyed around Guam during MARAMP 2005 and at all REA sites surveyed during MARAMP 2007. For more information about these benthic composition surveys, see "Line-point-intercept Surveys" in Section 2.4.5: "Corals and Coral Disease" in this chapter.

Voucher Specimens

At each REA site, algal voucher specimens were collected from a 2-m swath on either side of the same two 25-meter transects surveyed during the photoquadrat surveys. Samples were brought back to the laboratory for qualitative species identification at the microscopic level to assemble comprehensive species lists for each site. Voucher specimens were collected at all sites, even when environmental conditions (e.g., strong currents or surge) did not allow for the completion of the quantitative photoquadrat protocol. Voucher specimens and benthic images from photoquadrat surveys form a permanent record of algal communities at each REA site.

Figure 2.4.6a. An algal assessment team of 2 divers conducts photoquadrat surveys at a REA site on a reef at Guam. *NOAA photo by Jean Kenyon*



Coralline-algal Disease

Coralline-algal diseases and syndromes were quantified in tandem with surveys for coral disease using the belt-transect method at each REA site. Coralline-algal diseases were first surveyed during MARAMP 2007. These surveys were performed by 1 diver from the coral team.

At each REA site, the density of coralline-algal disease was assessed along two 25-m transect lines. At the beginning of each dive, subjectively perceived abundance of coral disease dictated the width of the belt: 2 m at disease-rich sites or where surge, currents, or rough seas precluded expanded surveys or 6 m at all other sites to tally a suffient number of cases of low-occurring incidences.Within belt transects, all afflictions to coralline algae were enumerated and classified into 3 general categories: coralline lethal orange disease, coralline white band syndrome, and coralline cyanobacterial disease. To avoid spreading diseases, when sampling within a disease site, collections of apparently unaffected (healthy) individuals were conducted first, followed by collections of portions of diseased plants that appeared unaffected (healthy on disease), and the diseased portions (lesions) of a plant were sampled last. Also, upon return to the ship, collection tools and dive gear were rinsed in bleach solution, thoroughly rinsed with freshwater, and air dried.

Descriptions of coralline-algal disease states are provided in the paragraphs that follow. For each REA site, density of coralline-algal disease was estimated, in lieu of prevalence, as the number of cases (counts) per 100 m^2 of reef area surveyed at that site: D = (total number of cases of a specific disease × 100) ÷ (total area surveyed for presence of disease).

Coralline Lethal Orange Disease

The distinguishing characteristic of coralline lethal orange disease is a band of bright orange, slimy material spreading across an algal surface, leaving behind bare skeletal carbonate remains of coralline algae. Motile rods of colonial bacteria have been detected through microscopic examination of this orange material but are yet unidentified (Littler and Littler 1995). Additionally, when this orange material has been transferred to other coralline algae, the same disease symptoms have been witnessed. Orange globules can be caught by waves and easily spread to nearby colonies.

Coralline White Band Syndrome

First discovered in the Caribbean, coralline white band syndrome was the second coralline-algal disease ever described (Ballantine et al. 2005). Lesions are characterized by white or pale yellow, irregularly shaped patches or bands spreading across the surface of coralline algae. Left behind are bare carbonate skeletal remains.

Coralline Cyanobacterial Disease

Coralline cyanobacterial disease is characterized by irregularly shaped patches or bands of slimy, fuzzy, green-to-tan cyanobacterial material spreading over algal surfaces, leaving behind bare skeletal carbonate remains; turf and filamentous algae often colonize bare coralline tallus. Lesions commonly are distinguishable by the conspicuous appearance of a cyanobacterial mat and by bright red, orange, or green discolored coralline algal tissue observable in areas where a mat has been lifted or disrupted (Vargas-Ángel 2010).

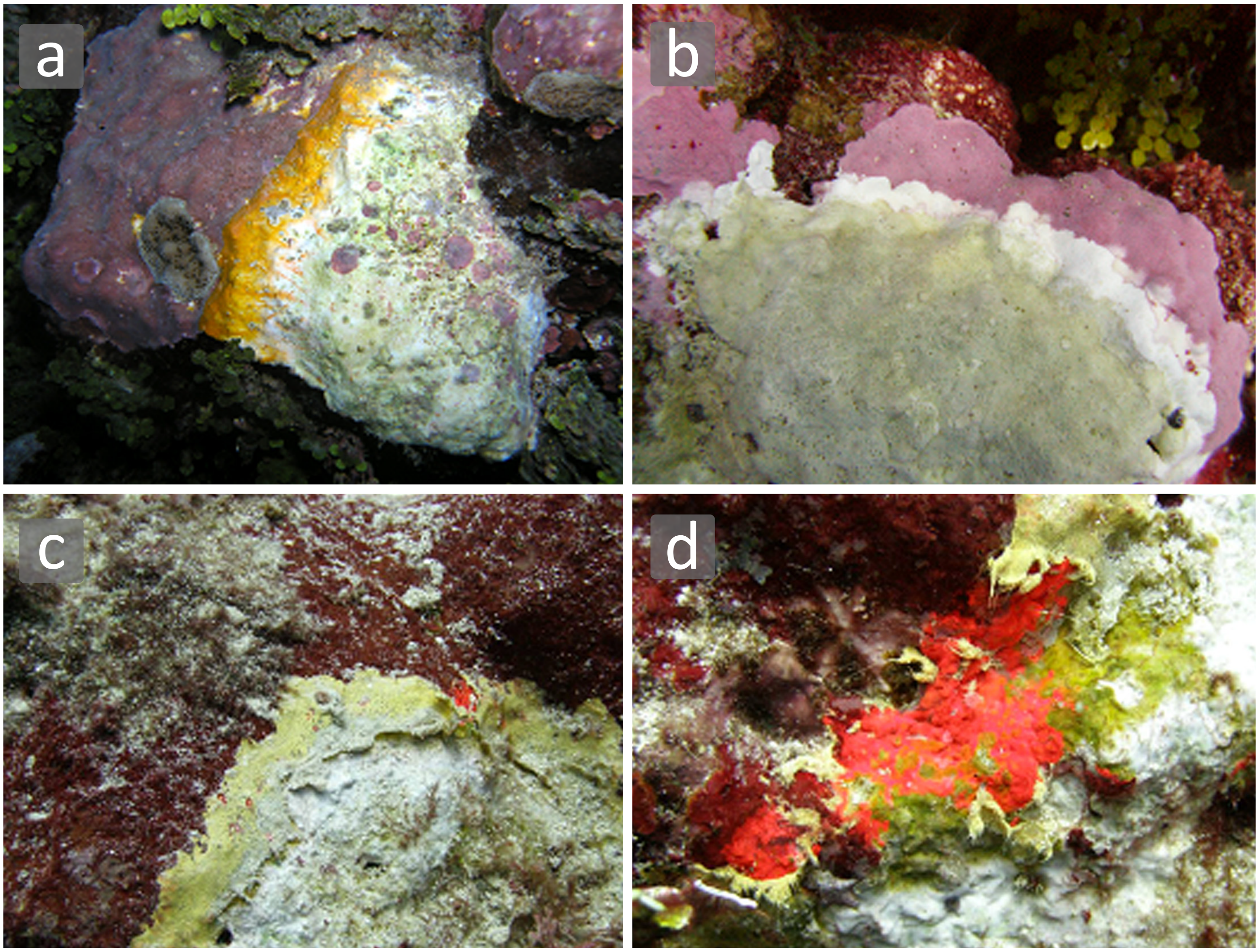


Figure 2.4.6b. Underwater photographs illustrating the field appearance of diseases affecting encrusting coralline algae around Guam and the CNMI during MARAMP 2007: (*a*) coralline lethal algal disease, (*b*) coralline white band syndrome, and coralline cyanobacterial disease, note (*c*) the green-colored cyanophyte mat overgrowing this algal surface and (*d*) the conspicuous, bight red and green color of this exposed, underlying coralline tallus. *NOAA photos by Bernardo Vargas-Ángel*

2.4.7 Benthic Macroinvertebrates

Macroinvertebrate surveys focused on targeted noncoral invertebrates that are common to the reef habitats of the Mariana Archipelago and used both REA and towed-diver methods during MARAMP 2003, 2005, and 2007. Survey results for 4 groups of ecologically and economically important macroinvertebrates—giant clams, COTS, sea cucumbers, and sea urchins—are provided in this report. High densities of the corallivorous COTS can affect greatly the community structure of reef ecosystems. Giant clams are filter feeders that are sought after in the Indo-Pacific for their meat, which is considered a delicacy, and for their shells. Sea cucumbers, sand-producing detritus foragers, are harvested for food. Sea urchins are important algal grazers and bioeroders and are harvested for food.

During towed-diver benthic surveys, divers recorded a suite of information at 5-min intervals that included counts of key conspicuous macroinvertebrates encountered within a survey swath that was 10 m wide (5 m on either side of the survey track), as well as estimates of habitat complexity and cover percentages of benthic substrate types. Macroinvertebrates, except COTS, were counted singly up to 25 and then binned as follows: 26–50, 51–100, 101–250, 251–500, 501–1000, and > 1000 organisms. COTS were counted singly up to 100 organisms, and then binned into the same higher classes. When considering survey results from towed-diver surveys, keep in mind that cryptic or small organisms can be difficult for divers to see, so the density values presented in this report, especially of giant clams and sea urchins, may under-represent the number of individuals present.

At each REA site, surveys were conducted by 3 dive teams, 1 of which consisted of 1 macroinvertebrate biologist and 2 algal biologists who performed macroinvertebrate and algal surveys. About 10 min after the coral team entered the water, the combined macroinvertebrate and algal team entered the water and began to work along the first of 2 or 3 transect lines (Fig. 2.4.1a).

Depending on the MARAMP survey year and region, up to 3 different REA survey methods were used to quantify diverse noncoral invertebrate communities during MARAMP 2003, 2005, and 2007: belt transect, quadrat, and roving diver (Tables 2.4.7a and 2.4.1b). Of the REA data collected, only belt-transect data is presented in this report because it was the most consistent REA survey type for all years. Belt-transect surveys were used to calculate macroinvertebrate densities for each REA site.

Note that REA methods recorded invertebrate species that are generally noncryptic (i.e., visible) and easily enumerated during the course of a single scuba dive. Therefore, these surveys documented only the noncryptic fauna of the reef habitat and should not be considered exhaustive for each site. Also, many invertebrate species are nocturnal and, thus, unlikely to be observed during MARAMP surveys, which are conducted during daylight hours.

Temporal comparisons of data from REA surveys are not presented in this report because of differences in procedures. During MARAMP 2003 and 2007, large mobile species were enumerated along transect lines. During MARMP 2005, the diver first conducted quadrat surveys, recording all species seen within 0.25-m^2 quadrats, then conducted belt-transect surveys, recording only organisms along each transect line that were not seen in the quadrat surveys done on that same transect, and, finally, conducted roving-diver surveys, recording only organisms seen on or up to 5–12.5 m on either side of each transect line. Therefore, densities from transects surveyed in 2005 may have been lower, versus densities recorded in 2003 or 2007, if the diver recorded large mobile taxa within quadrats first. In addition, invertebrate surveys were not conducted at Guam, Saipan, Tinian, Aguijan, or Rota in 2007 because of the lack of an available, experienced invertebrate diver.

Belt-transect Surveys

The belt-transect method was used to record quantitative invertebrate counts along two 25-m transects with a survey width of 2 m or three 25-m transects with a survey width of 4 m. Species searched for along these belt transects included noncryptic, mobile taxa: anemones, echinoids, holothurians, crinoids, asteroids, urchins, large gastropods, cephalopods, and large crustaceans. Tridacnid bivalves (*Tridacna* spp.) also were counted.

Quadrat Surveys

The quadrat method was used to quantify smaller, more cryptic macroinvertebrates that were sometimes overlooked or too numerous to count during belt-transect surveys. Divers enumerated organisms within a quadrat (0.25 or 1 m^2) that was either haphazardly placed or numerically aligned every 5 m along each transect line.

Roving-diver Surveys

The roving-diver method was used with the goal of observing invertebrates not seen during belt-transect surveys. During MARAMP 2003 and 2007, roving divers recorded as "present" invertebrate species observed as they haphazardly swam in the vicinity of a transect searching for species. During MARAMP 2005, roving divers swam a zigzag pattern extending 5–12.5 m to either side of both 25-m transect lines.

Survey Method and Transects	2003		2005		2007
	CNMI	Guam	CNMI	Guam	CNMI
Number of Transects (per site)	2	2	2	2	3
Belt Transect	25 × 2 m	25 × 2 m	25 × 2 m	25 × 2 m	25 × 4 m
Quadrat	–	–	0.25 m^2 (interval placement)	0.25 m^2 (interval placement)	1 m^2 (haphazard placement)
Roving Diver	haphazard swim	haphazard swim	25 × 25 m	10 × 25 m	haphazard swim

Table 2.4.7a. Number of transect lines per site and survey area per transect or quadrat for the 3 types of REA macroinvertebrate surveys conducted during MARAMP 2003, 2005, and 2007. REA macroinvertebrate surveys were not conducted around Guam, Saipan, Tinian, Aguijan, or Rota in 2007.

2.4.8 Reef Fishes

Reef fish communities were assessed using both REA and towed-diver surveys during MARAMP 2003, 2005, and 2007. Biomass and abundance per unit area of large fishes (≥ 50 cm in total length [TL]) were assessed using towed-diver surveys. During all MARAMP survey years, the same 3 complementary REA methodologies—belt transect, stationary-point count, and roving diver—were used to estimate the diversity (species richness), numeric abundance (number of fish per 100 m^2), and density (biomass in kg 100 m^{-2}) of diurnally active reef fish assemblages.

During towed-diver fish surveys, divers conducted a 360° scan during the first minute of each 5-min survey segment, recording all large fishes (≥ 50 cm in TL) within their range of visibility. During the remaining 4 min of each segment, all large fishes that appeared within a survey swath that was 10 m wide (5 m to either side of the towline) and 10 m in front of the diver were recorded. During MARAMP 2007, the 360° scan was removed from the survey method, with all 5 min of each segment used to assess large-fish populations forward of the diver and within the survey swath. This report presents data from observations recorded during the last 4 min of each segment in 2003 and 2005 and the entire 5 min of each segment in 2007.

Results from towed-diver fish surveys were used to calculate estimates of large-fish biomass, as weight per unit area, for each survey and ultimately for each island. The length of each individual fish was determined visually and each individual was assigned to predetermined size classes. Large-fish biomass was calculated for each towed-diver survey by applying the midpoint length for each size class to published length-weight relationships ($w = a \times L_b$) for individual species (Kulbicki et al. 2005). When species-specific length-weight formulas were not available, formulas available for the best comparable species (genera, body type, etc.) were used. Large-fish sightings were summed for each survey segment and used to calculate estimates of total fish biomass per survey as well as biomass by fish family.

Towed-diver fish surveys also allowed for "snapshot assessments" of very large fishes (e.g., sharks, jacks, and barracudas) and schools of various species whose range and abundance may be difficult to reliably census during fine-scaled, area-limited REA surveys. In addition, species of concern observed outside a survey swath were recorded as "present," and this data was handled separately from the quantitative towed-diver-survey data.

A forward-facing Sony DCR-PC1000 digital video camera was attached to fish towboards and used to collect streaming video images on Mini DV. To document habitats, video footage from these forward-facing cameras was archived as a durable record of the towed-diver-fish-survey track.

At each REA site, surveys were conducted by 3 dive teams, 1 of which consisted of 2–3 divers who performed fish surveys. The fish team was the first team to enter the water at each REA site. The fish team deployed the first 25-m transect line (Fig. 2.4.1a), and 2 divers began to survey along that transect while the remaining fish diver began stationary-point-count assessments in the general vicinity of that transect (if only 2 divers, then SPC surveys were not done). By the time the coral team entered the water ~ 20 min later, the fish team had deployed and begun surveys along a second 25-m transect. After completing the second transect, the fish team moved on to the third transect.

During all 3 types of REA fish surveys, fishes of all sizes were identified to the lowest taxonomic level possible, generally species, and assigned to standard bins according to their size: 1-cm bins for fishes < 5 cm in TL (0–1, 1–2, 2–3, 3–4, and 4–5 cm) and 5-cm bins for fishes > 5 m in TL (e.g., 5–10 and 10–15 cm). During belt-transect and stationary-point-count surveys, all reef-associated fishes, including those in the water column (e.g., planktivores), were counted, and coastal pelagic species (e.g., clupeids [sardines], belonids [beakfishes], and antherinids [silversides]) seen near the ocean surface were not recorded.

Results from belt-transect surveys at REA sites were used to calculate the estimates of total fish biomass provided in this report. Fish counts from belt-transect surveys were converted to biomass estimates (kg 100 m^{-2}) using length-weight relationships as explained for towed-diver surveys. Data collected from belt-transect surveys also were used to calculate values of species richness (number of species per 100 m^2) at each site. Data from stationary-point-count and roving-diver surveys are not presented in this report.

Belt-transect Surveys

Using the belt-transect method at each site, three 25-m transects lines were surveyed by a pair of divers in 2 passes. On the first (outward) pass, divers swam side-by-side recording all fishes ≥ 20 cm in TL that were observed within adjacent belts, both with widths of 4 m. Thus, the total transect width surveyed by both divers together was 8 m, and the area surveyed per outward swim was 200 m^2 (8 × 25 m). Upon completing the outward component of a survey, divers turn around and swim back down the same transect, recording all fishes < 20 cm in TL that were observed within adjacent belts with widths of 2 m (total survey area = 100 m^2). Survey dimensions were determined following methodological trials by staff from NOAA National Marine Fisheries Services before the onset of the Pacific RAMP and have been standards for CRED throughout its existence. The outward survey of large fishes took ~ 5 min to complete per transect, while the return survey of small fishes took ~ 10 min to complete per transect.

Stationary-point-count Surveys

The stationary-point-count method (Bohnsack and Bannerot 1986) was used to quantify large and mobile reef-fish species that can be difficult to survey by means of belt transects. For each stationary-point-count survey, 1 diver swam ~ 15 m away from the transect line that the other 2 divers were concurrently surveying. The diver then recorded all fishes > 25 cm in TL that passed within a visually estimated cylinder with a 20-m diameter centered on that diver's fixed position (total survey area = 314 m^2). The species and size, in 5-cm bins, were recorded for each fish. At each REA site, 4 stationary-point-count surveys were conducted, each taking ~ 5 min to complete.

Roving-diver Surveys

The roving-diver method was used to record the presence, generally to species level, of reef-fish taxa not encountered during previous surveys using the other methods. Following belt-transect and stationary-point-count surveys, as diver bottom-time permitted, the fish assessment team conducted random swim surveys throughout the area of a REA site.

2.4.9 Protected Species

As part of towed-diver surveys, divers recorded sightings of sea turtles (Cheloniidae) and other species of concern in addition to the main suite of information on fish communities and benthic composition. Sea turtles were tallied and their size estimated by towed divers whenever they were observed during a survey. Recorded sightings were not limited to the 10-m survey swath (or width) of a towed-diver-survey area. Species of concern observed outside a survey swath were recorded as "present," and these data were handled separately from the quantitative towed-diver-survey data.

Divers who had not conducted towed-diver surveys, such as divers who had conducted REA surveys, collected hydrographic data, or deployed instruments, on a daily basis reported incidental observations of species of concern. During MARAMP 2003, in addition to the regular towed-diver surveys, up to 2 towed divers performed surveys dedicated to turtle observations (Kolinski et al. 2005).

2.4.10 Marine Debris

As a secondary data set, towed-diver surveys included numeric recording of benthic anthropogenic marine debris. The secondary nature of this marine debris data set means that observations may have been omitted by a diver because of other data priorities at a given time. Therefore, data presented here can be qualified as regional underestimates. Observations of debris presented in this report are positive identifications, but absence of reports does not imply lack of debris.

Towed-diver surveys numerically tallied marine debris when sightings fell within the 10-m width of a survey swath for each 5-min survey segment. Debris items included but were not limited to the following types: (1) derelict fishing gear, (2) munitions, or unexploded ordinances, (3) shipwrecks, and (4) other man-made objects, whether of nautical or terrestrial origins. Debris sightings were recorded differently during MARAMP 2003 than during the other survey periods: sightings in 2003 were recorded as a direct part of diver observational methods, and sightings in 2005 and 2007 were recorded solely as incidental observations by the towed divers in their observer comments.

2.5 Ecosystem Integration: Coral Reef Condition Index

The *Coral Reef Condition Index* is a composite metric of biological variables that describes the relative status of coral reefs throughout the Mariana Archipelago. This integrated condition index is composed of a benthic category and a fish category, both of which contain multiple biological components (Fig. 2.5a). This approach provides a way to evaluate the condition for the fish and benthic categories individually, using the *Benthic Condition Index* and *Fish Condition Index*, as well as the overall coral reef condition for a given area. All index variables are based on observations from towed-diver surveys. The benthic category is made up of 5 components: cover of live hard corals, cover of stressed corals, cover of macroalgae, cover of crustose coralline red algae, and density of crown-of-thorns seastars (COTS). The fish category comprises 2 components: density and biomass, both of large fishes (≥ 50 cm in TL).

Analysis for the Coral Reef Condition Index was conducted at 2 spatial scales, archipelagic and island levels, using data collected during MARAMP 2005 and 2007 towed-diver surveys. Geographic regions were the unit of analysis for archipelagic comparisons. Geographic regions are delineated on map figures as 1.5-km buffers from the 100-fm isobath around each island with breaks determined by differences in coastal wave exposures and the spatial extent of MARAMP survey locations. Analysis on the island scale was performed using data from surveys around only the 4 populated, southern islands of Guam, Rota, Tinian, and Saipan and towed-diver-survey areas as the unit. For the island-level indices, survey areas are represented on map figures by irregular polygonal buffers derived from towed-diver-survey tracks that overlapped in 2005 and 2007 (survey tracks were often similar but not exactly the same in each survey year). For the archipelagic indices, polygons are shaped by the geographic regions. These geographic-region and survey-area polygons do not reflect the actual area surveyed but rather provide a useful, enlarged visualization of index results for data collected within geographic regions and survey areas.

Towed-diver surveys allow for a rapid and quantitative survey over a broad area (see Section 2.4: "Reef Surveys: Corals, Algae, Macroinvertebrates, Fishes, and Substrates"). The 7 index components were chosen to describe the condition of coral reef ecosystems within geographic regions and survey areas. Because of differences between years in towed-diver-survey methods, data from MARAMP 2003 surveys were not included in the Coral Reef Condition Index or its associated fish and benthic categories. In addition, data from geographic regions and survey areas where surveys were conducted in only a single year were not analyzed.

Each of the 7 components was rank-transformed from survey mean values. At the archipelagic scale, ranks were assigned to each geographic region based on mean survey segment values. At the island scale, ranks were assigned to each survey area based on mean survey values. The advantages of this method include simplicity and independence to outliers. The primary disadvantage of this method is that it loses the absolute value of information, although the ranges of component values for each year are presented to evaluate overall absolute changes.

The ranks in these condition indices are presented on maps to allow for comparisons and visual representation of spatial and temporal patterns across the Mariana Archipelago or among the 4 populated, southern islands of Guam, Rota, Tinian, and Saipan. To create these maps, index ranks for geographic regions and survey areas were separated into tertiles categorized as "high," "medium," and "low." Temporal patterns in index tertiles provide a simplified and conservative means to track relative conditions of biological resources, such as "improving," "declining," or "unchanged."

A high rank means superior condition relative to (a), in the archipelagic indices, other geographic regions in the Mariana Archipelago or (b), in the island-level indices, other survey areas in the 4 populated, southern islands. Coral reef areas with high ranks in the Coral Reef Condition Index were characterized by relatively high values of coral cover, crustose-coralline-red-algal cover, fish density, and fish biomass as well as low values of stressed-coral cover, COTS density, and macroalgal cover. Coral reef areas with low ranks in the Coral Reef Condition Index have relatively low values of coral cover, crustose-coralline-red-algal cover, fish density, and fish biomass as well as high values of stressed-coral cover, COTS density, and macroalgal cover.

The *Archipelagic Coral Reef Condition Index* is the basis for comparing ecosystems across the Mariana Archipelago, particulary between the southern islands and the northern islands, in Chapter 3: "Archipelagic Comparisons." The *Coral Reef Condition Index for Guam, Rota, Tinian, and Saipan* is used to compare survey areas around those individual islands and among them in the "Ecosystem Integration" sections of Chapters 4, 5, 7, and 8.

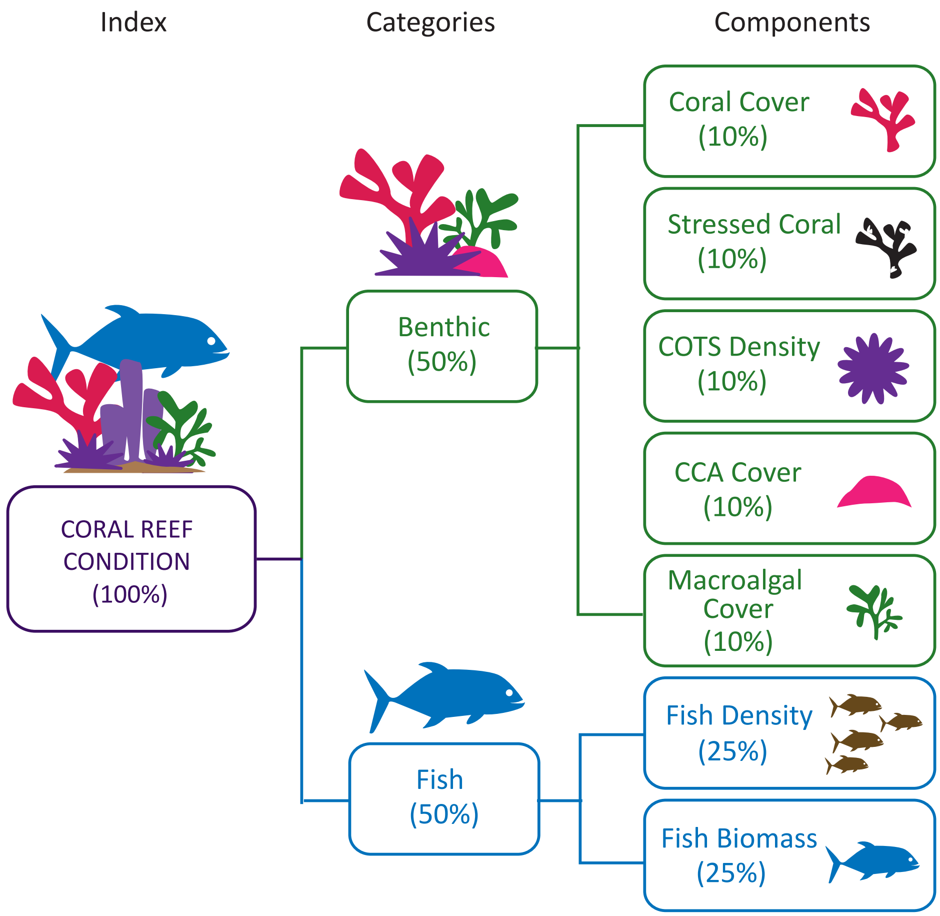


Figure 2.5a. Schematic of the categories and components of the Coral Reef Condition Index, which uses equal weights on the benthic and fish categories. Actual weights are shown in parenthesis.

Formally, the variables and components were aggregated additively with a summation of weighted and normalized components (Fig. 2.5a):

$$I_j = \sum_{i=1}^{N} w_i \, x_{ij}$$

where I_j is the composite index for j, a geographic region or survey, x_i is a variable, and w_i is the weight of the variable, x_i, with $\sum_i w_i = 1$ where $0 \le w_i \le 1$, for all $i=1,\ldots,N$ and $j=1,\ldots,M$. The Coral Reef Condition Index uses an equal average weighting method between the benthic and fish categories. Coral cover, crustose-coralline-red-algal cover, fish density, and fish biomass were rank-transformations of raw variables.

2.6 Geographic Information System Products

All map-based figures included in this report were generated with ESRI's ArcGIS 9.3 desktop Geographic Information System (GIS) software to characterize spatial variability of survey data collected primarily during MARAMP 2003, 2005, and 2007. Geographic data incorporated in maps include multibeam bathymetry and backscatter products and derivatives, TOAD survey tracks, locations of REA and towed-diver surveys, and other baseline geographic features.

These geographic data are stored and managed in an enterprise geodatabase via ESRI's ArcGIS Server 9.3 and Oracle Database 10g (Redwood Shores, Calif.). All nongeographic data (e.g., TOAD habitat classifications, physical and chemical oceanographic properties, and observations from REA and towed-diver surveys) are stored and managed in CRED's relational database management systems.

Nongeographic data were plotted in ArcGIS using 1 of 2 methods: (1) joining nongeographic data to their corresponding survey locations via a common field (e.g., towed-diver fish observations to towed-diver-survey tracks using the unique serial numbers for each survey) or (2) directly plotting the latitude and longitude of each observation or measurement (e.g., temperature from shallow-water CTD casts) using the *Add XY data* function in ArcGIS.

Data are displayed within ArcGIS using a number of different methods, depending on whether the type of geographic data is vector or raster. The vector data model uses 2-D coordinates to store and represent geographic features as points, lines, polygons, or areas (Heywood et al. 2002). The raster data model defines space as an array of equally sized cells arranged in rows and columns in which each cell contains an attribute value and location coordinates (Heywood et al. 2002; ESRI 2009).

REA survey sites (points), towed-diver-survey tracks (lines), and geographic regions (polygons) are examples of vector data. The following methods, among others, were used to display vector data in this report:

- Features: single symbol
- Categories: unique values
- Quantities: graduated colors and graduated symbols using the natural breaks (Jenks), equal interval, or manual classification methods
- Charts: pie and bar

Multibeam bathymetry and backscatter products and derivatives are examples of raster data. The following methods, among others, were used to display raster data in this report:

- Unique values
- Classification using the natural breaks (Jenks) or manual classification methods
- Stretched